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Pull and Leakage Flux Characteristics of a Large Solenoid

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PULL AND LEAKAGE FLUX CHARACTERISTICS OF A LARGE SOLENOID

BY

ERNEST ALEXANDER REID

B.S. University of Illinois, 1914

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN ELECTRICAL ENGINEERING

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1915

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Ernest Alexander Reid

ENTITLED Full and Leakage Flux Characteristics of a Large Solenoid

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering

Ellery B. Paine
In Charge of Thesis

Ellery B. Paine
Head of Department

Recommendation concurred in:*

Committee
on
Final Examination*

*Required for doctor's degree but not for master's.

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I. INTRODUCTION.

In view of the increasingly widespread use of electromagnets for remote control apparatus and similar devices, and the fact that few tests have been published concerning them, an attempt has been made in this thesis to determine the pull characteristics, under various conditions, and the distribution of the magnetic field of an ironclad solenoid of the plunger type.

The pull required to separate two plungers in a long solenoid, when the ends are at the center of the winding and perfectly joined magnetically, is, according to Maxwell's equation,

$$P_m = \frac{B^2 A}{8\pi} ,$$

where P_m is the pull in dynes, B is the flux density in the plungers, and A is the area of the plunger section. Reduced to kilograms, this becomes,

$$P_m = \frac{B^2 A}{8\pi \times 981000} . \qquad (1)$$

When the plungers are separated, this equation no longer holds since, instead of having a single electromagnet, we now have the equivalent of three electromagnets. Each plunger and the air gap have a field similar to that surrounding a permanent bar magnet. Underhill has shown this clearly by means of iron filings. For this reason, he has divided the static pull of a solenoid with plunger and stop into two parts: that existing between solenoid and plunger, and that existing be-

tween stop and plunger. A pull also exists between solenoid and stop, but the stop is assumed to be fastened rigidly, hence the last pull is not an effective one.

Now assuming that the entire reluctance of the magnetic circuit is in the air gap, (1) reduces to

$$P_m = A\left[\frac{IN}{3951\ l}\right]^2, \tag{2}$$

P_m is the pull in kilograms, l is the length of the air gap in cms., and IN is ampere-turns. Also, from the fact that the solenoid pull is proportional to 2H(B-H), Underhill works out this part of the pull to be

$$P_s = \frac{IN\ \theta_t A}{981\ L}, \tag{3}$$

where L is the length of the solenoid and θ_t is the factor to be multiplied by $.2\pi IN$ to give the value of H at the center of the winding. Evidently θ_t has a maximum value of 2, and Underhill expresses it for other values by the empirical formula

$$\theta_t = 2 - \frac{r_a}{1.07\ L}. \tag{4}$$

r_a is the average radius of the solenoid . (4) seems logical since for a very long solenoid of small radius, $\theta_t = 2$, and hence $H = \frac{.4\pi NI}{L}$, which agrees with the theoretical value for the field at the center of a very long solenoid of small radius. (3) is deduced on the assumption that $B - H = 20000$ lines per sq. cm. This is a fair value for saturated plungers of soft iron or steel.

So far, the losses due to the ampere-turns required to saturate the plunger have not been considered. By calling

this loss λ, (3) becomes

$$P_s = \frac{A\theta_t\,(IN - A\lambda)}{981\ L}\ , \qquad (5)$$

and the entire pull

$$P = A\left[\frac{\theta_t\,(IN - A\lambda)}{981\ L} + \left(\frac{IN}{3951\ l}\right)^2\right]. \qquad (6)$$

From (6) it is seen that as the air gap increases, the pull due to the stop decreases rapidly. It would also appear that with zero air gap the pull would be infinite. This is due to the error introduced in assuming that all of the reluctance of the magnetic circuit is in the air gap between plunger and stop. For small air gaps, then, this formula will not hold unless the reluctance of the remainder of the magnetic circuit is considered.

II. APPARATUS.

The Solenoid. Since no definite duty was to be performed by the solenoid, the actual pull was of no particular importance in the design. A large solenoid was desired, so that conditions such as exist in commercial magnets might be investigated. Hence certain dimensions were first assumed and adhered to insofar as commercial materials could be secured.

A plunger of two inch diameter was chosen. Investigations have shown that the plunger diameter should be approximately one-third the coil diameter, hence the latter was made six inches. After calculating the size of wire to be used, it was found that a coil length of eighteen inches would give the desired space for about 18000 ampere-turns. This number was approximately the correct value needed in order that the plunger might always be saturated. The above dimensions were taken as the basis of the design.

A brass tube of two inch interior diameter and 1/16 inch thickness was secured, and the plunger and stop turned to a sliding fit. The plunger was made 22" in length and the stop 12". The former was then long enough to go entirely thru the solenoid, and the latter could be placed in any position up to the center of the winding. The shell was made from a piece of 6" wrought iron steam pipe. It was cut to a 21" length, and bored out to a smooth finish inside. The final dimensions were: inside diameter 6 3/16"; outside diameter 6 9/16". Castings were made for the heads and these were bored and

turned to the dimensions shown in Figure 1.

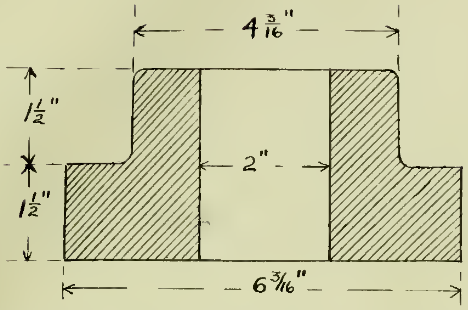
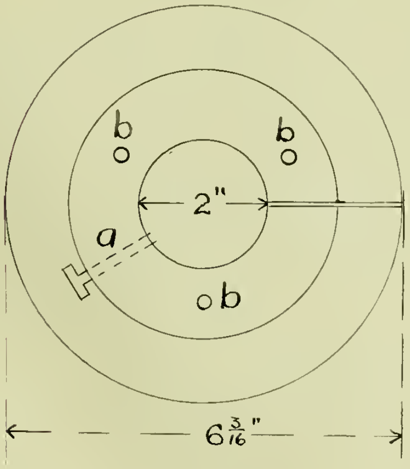


Fig. 1.

The heads were similar except that the upper one was bored out to a 2 1/8 instead of a 2 inch hole. This was done in order that the brass tube might pass thru to prevent sticking of the plunger. Since the stop fitted snugly into the lower casting, there was no necessity of having the tube pass thru it. All joints between parts of the iron circuit were made smooth. A ¼" slit was cut the entire length of the shell. The lower casting was cut as shown in Figure 2. Stop, casting, and shell were then held tightly against one another by a clamp illustrated in Figure 3.



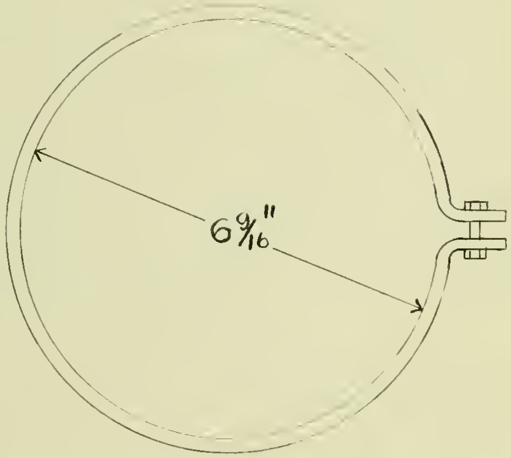


Fig. 2.

Fig. 3.

The stop was further secured by a 3/8" set screw "a".

The solenoid was held to the platform by screws fitting into the three tapped holes "bbb".

It will be noted that the plunger cross-sectional area was 3.14 sq. in. The shell area was approximately 3.7 sq. in. This insured a return path of equal or less reluctance than that of the plunger. The cast-iron heads were made with a large cross-sectional area, and in the magnetic joints, where an air gap was introduced, the area was made large. The only air gap of importance in the magnetic circuit, aside from the variable one between plunger and stop, was between the upper head and the plunger. Here the area was 20 sq. in., so the reluctance was only 8 percent of the reluctance of an eighth inch gap between plunger and stop. Hence with increasing air gap length, the reluctance of the remaining magnetic circuit soon became negligible.

The coil was wound in six sections for three reasons: (1) better insulation for high induced voltages; (2) in order to vary the length of the solenoid; and (3) that search coils might more easily be inserted for mapping out the magnetic field. Trial calculations showed that No. 17 B.& S. guage double cotton-covered wire would give the maximum ampere-turns -with allowable heating- in the given space. Calculations were as follows:

Total winding space ----------------- 18" x 2 1/32"
Winding space per section ------------ 3" x 2 1/32"
Less .012" for tape ------------------2.976" x 2.007"
Less .076" and .1" for fitting ------- 2.9" x 1.907"

No. 17 wire d.c.c. allows 18.87 turns per inch.

Turns in 2.9" ---------------------- 54.7

Turns in 1.907" ---------------------36

Turns per section ------------------ 1970

Total turns --- 1970 x 6 ----------- 11820

Steady current carrying capacity with given
radiating surface ------- approx. 1.52 amp.

Total ampere-turns ----------------- 18000

Total resistance ------------------- 71.5 ohms.

Voltage necessary ------------------ 108.

Weight of wire required ------------ 80 lbs.

A form was made and each section carefully wound and taped. The final result checked very closely with the calculated as to number of turns, 11900 being put on instead of the calculated 11820. After being removed from the form and taped, each coil was baked in an oven at about 90° C. for twelve hours, then soaked in orange shellac for about the same length of time, and finally dried for another twelve hours in the oven. The coils maintained their shape perfectly, and were capable of withstanding fairly rough handling.

Search Coils. It was desired to ascertain what portion of the flux leaked out thru the coil with various air gaps, and for this purpose it was decided to measure the flux in planes both parallel with and vertical to the plunger axis. Since the plunger had an area of 20.3 sq. cms., and as about 21000 lines per sq. cm. gives saturation for commercial wrought iron, a maximum value of flux equal to about 400000 lines was assumed. Since a Grassot fluxmeter, having a capacity of

reading 1000000 leakages was to be used, it was seen that a single turn of wire for each search coil would be sufficient. The problem of placing and holding these turns in place so that the exact position would be known was solved by sewing No. 36 double silk covered wire into thin varnished cambric cloth, cut to fit over the brass shell and inside the iron shell. A sketch of a finished plate, with dimensions, is shown in Figure 4.

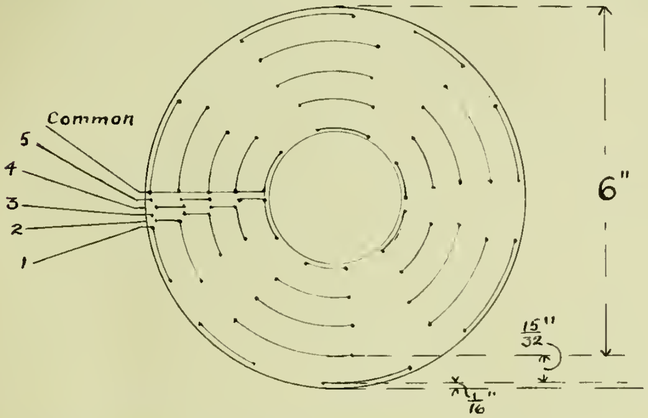


Fig. 4.

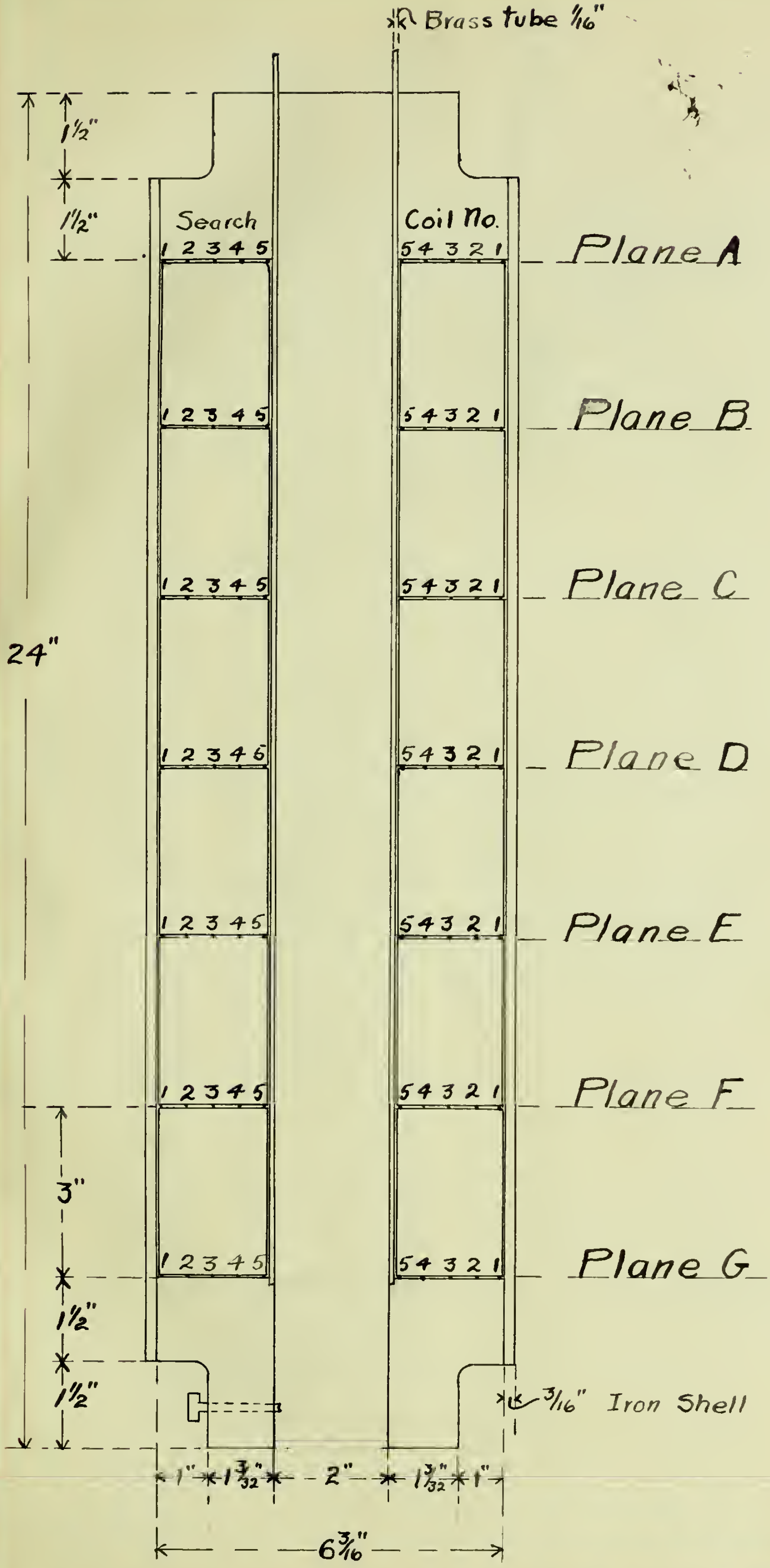
Coil 5 was 1/8" from the plunger, and each succeeding coil was 15/32" from the preceding one. Coil 1 was 2" from the plunger. One end of all the coils was made common. One plate was placed between each two sections of the main coil, and one at the top and bottom of the first and last coils respectively. This arrangement is shown clearly in Figure 5, which shows a vertical cross-section of the assembled solenoid. The leads were encased in rubber tubing and brought out thru the slit in the shell to a terminal board. Each terminal was soldered to the head of a brass screw. The screws passed thru the board, and snap connectors were used to connect the coils in turn to the flux-meter.

Weighing Apparatus. A scale, shown in Figure 6,

capable of weighing 1100 lbs. by increments of 1 lb. was purchased. It was mounted on an oak platform, 4" x 12" x 4', and the platform placed on a frame as shown in Figure 6. The remainder of the frame was of dressed 3" x 10" oak. The scale was connected to the solenoid by means of a turnbuckle and chain. Each link was 4½" inside length, and the turnbuckle gave a variation in length of 6" by as small increments as desired. Hence by the use of the turnbuckle and any particular link, the plunger could be placed in any desired position. The solenoid was set in a vertical position in order that errors due to friction might be eliminated. The great distance between solenoid and scale was necessary in order that all possible positions of the plunger in the solenoid might be obtained. Figure 6 shows a complete diagram, to scale, of the entire set-up, and Figure 7 a photograph of the same.

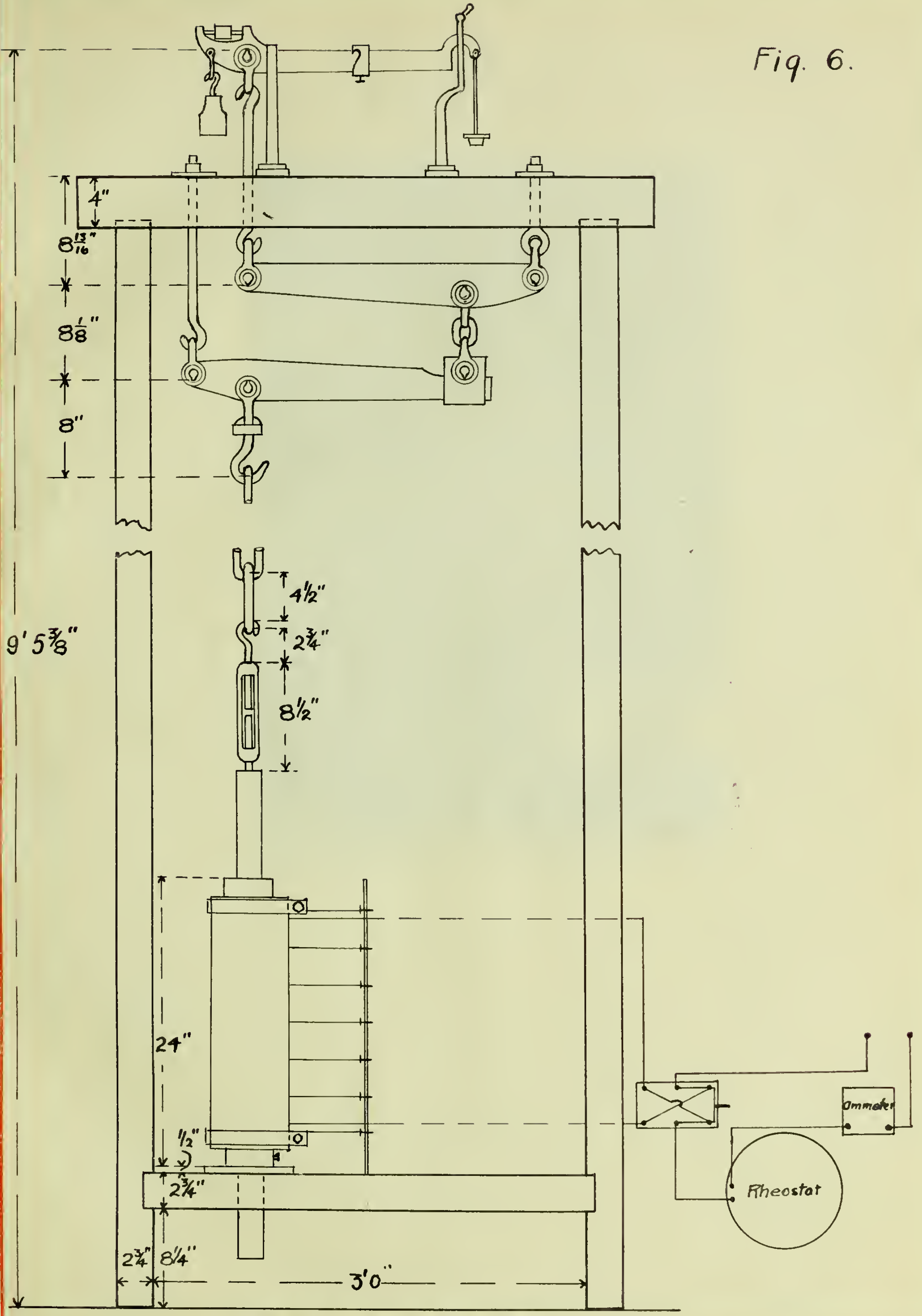
Electrical Connections. Direct current from 110 or 220 volt mains was run thru an ammeter and a rheostat to a double-pole, double-throw, reversing switch, and thence to the coil. The reversing switch was especially necessary in taking the flux readings. Its use in that connection will be explained under the experimental work.

Figure 5



Scale 1" = 3"

Fig. 6.



Scale: 1 inch = 1 foot.

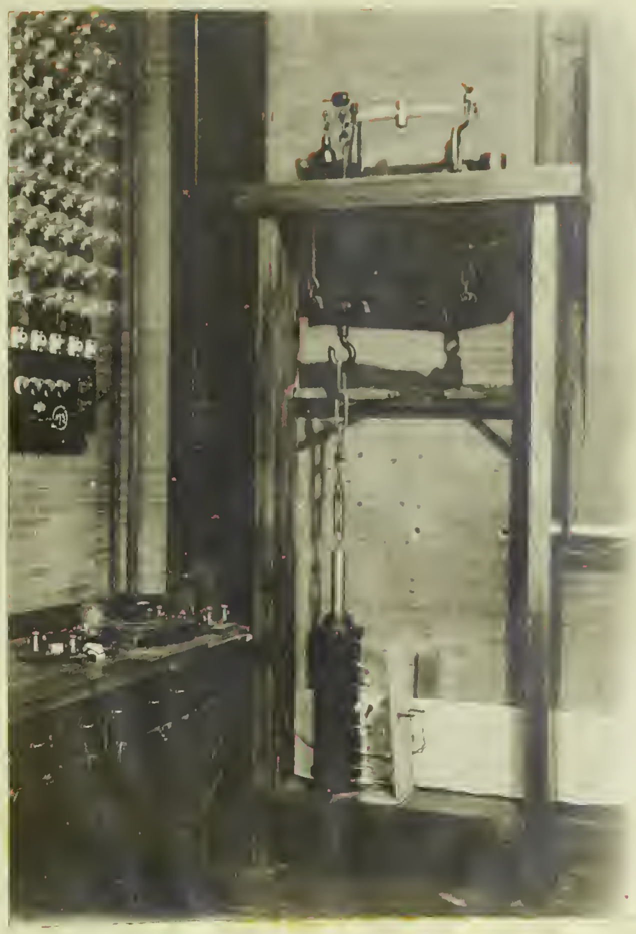


Figure 7.

III. EXPERIMENTAL WORK.

Pull Characteristics. With the stop fixed so that its upper surface was flush with the lower end of the coil, the plunger position was varied from a position in contact with the stop to a position just entering the coil; that is, from 0 air gap to 18" air gap. For each position, the ampere-turns were varied from 0 to 38000. Positions taken were with air gaps of 1/8", 1/4", 1/2", 1", 2", 4", 8", 12", 15", and 18" in turn. The curves given on Plate I were obtained.

The stop was moved up a distance of three inches; that is, it projected into the coil a distance equal to one-sixth the coil length. With the same increments as before, -up to 15" - the above tests were repeated, and the curves shown on Plate II obtained. The work was repeated with the stop six inches into the coil, or one-third its length; with the stop nine inches into the coil, or one-half its length; and with no stop. The air gap increments were the same in each case except that the maximum gap each time was taken with the plunger just entering the coil. The curves on Plates III, IV, and V were thus obtained. From these five plates, it is possible to obtain the pull for any of the five positions of the stop, for any magnetomotive force, and for any air gap length.

By cross-plotting, Plates VI, VII, and VIII were obtained. From these, for any given position of the stop, the pull may be found for varying air gap length, for four different excitations. In the same way, Plate IX is obtained, and

shows the pull for various plunger and stop positions with a constant magnetomotive force.

Flux Distribution. With the stop fixed as in the first test above, that is, flush with the lower end of the coil, and the plunger in contact with the stop, a reading of the flux cutting each of the thirty-five search coils was taken. The method of taking these readings was as follows:

The current in the main coil was built up to the desired value,- in this case 11900 ampere-turns,- and the switch opened. The flux-meter was then short-circuited, and the needle remained near the point of highest deflection. The switch was then closed on the main coil, the short circuit opened, and the switch quickly reversed. The reading obtained was due to the flux dying out in the coil and building up in the opposite direction. Half of this reading was the true value of the flux cutting the search coil. The advantage of reversing the excitation is evident, since otherwise the difference between total flux and residual would be obtained, instead of the total flux. Several reversals were made on each search coil. Since the flux-meter reading does not depend upon the resistance of the circuit, nor upon the time of opening or closing the switch, it can be seen that this method of taking the flux readings is accurate, provided that the meter itself is accurate. The meter was calibrated, and the current was carefully kept constant. The results are plotted on Plate X.

With the stop in the same position, the above tests were repeated with air gaps of 1/8", 1/4", 1/2", 1", 2", 3", 6", and 9". Plates XI to XVIII inclusive were thus obtained.

Plate XIX was obtained by setting the stop in the coil a distance of three inches, and setting the plunger with a three inch air gap. That is, the air gap was between Planes F and E of the search coils, the plunger surface being in Plane E while the stop surface was in Plane F. Plate XX was obtained by moving both plunger and stop up three inches, or, in other words, by putting the plunger surface in Plane D and the stop surface in Plane E.

To get the flux distribution in the center of the air gap, with the air gap in the center of the solenoid, plunger and stop were set in contact at Plane D, and the air gap increased by moving each the same distance from Plane D,- that is, half the given air gap. The flux cutting the coils of Plane D was then taken by the method outlined. Plate XXI shows these results.

IV. CONCLUSIONS.

Pull Characteristics. Plates I to V inclusive, showing the pull obtained with different positions of stop and with varying ampere-turns, are largely self-explanatory. It is seen that the contact pull is practically the same for any position of the stop. This would be expected, since the pull in that case is the pull between two magnets, and does not depend upon the position of the magnets in the coil. However, when a small air gap is introduced, it is seen that the maximum pull is obtained with the stop one-third the length of the solenoid, and falls off for positions on either side. Evidently , then, the pull will increase as the length of stop increases until some point near the center is reached, and then decrease for lengths beyond this. For air gaps beyond $\frac{1}{4}$" in length, the pull is practically the same for all positions of the stop, except for the position even with the coil. It appears, then, that for best results, the stop should enter the coil a short distance. Between this position and the center of the coil, the range is the same.

Plate V shows that the pull without the stop is much smaller than with a stop for air gaps below $\frac{1}{2}$", and about the same for longer gaps. This shows conclusively that the range thru which the stop is effective is quite small. In fact, unless the pull at the end of the stroke is to be taken advantage of, the stop may as well be eliminated.

On Plates VI, VII, and VIII, the pull with varying

air gap and different excitations, is shown for three positions of the stop. The effective range is here clearly indicated. The maximum length of effective range is with the stop just even with the coil. Here, a uniform pull is obtained for about 12", or for over .6 the length of the solenoid. This range is the same for various excitations. With the stop 1/6 and 1/3 the length of the coil, the pull is not so uniform over the effective range, nor is the range so long. If the length of the solenoid is taken as the length above the stop, then the range is still about .6 the length. From these curves, it is evident that when a uniform pull is desired thru a long range, the stop should not project into the coil. In fact, the effective range would be as good without the stop,- its only effect being to slightly increase the pull thruout the range. Of course, if the large pull at the end of the stroke is to be taken advantage of, the stop is necessary.

Plate IX shows these same effects in a different way. For a given excitation, the pull with varying plunger positions for different positions of the stop, is shown. These curves show again that practically the same pull is obtained for different positions of the stop, the only difference being in the increased range.

Flux Distribution. Plates X to XVIII inclusive show the paths of the flux with the stop even with the coil, and with varying air gaps. Remembering that search coil No. 5 is the coil which measures the flux thru the stop, plunger, and air gap; and that Plane G is the plane of the stop surface; it

is seen that the flux thru the stop decreases from 385000 lines when there is no air gap to only 155000 lines at 1/4" gap, 95000 lines at 1/2" gap, 50000 at 1" gap, and 15000 at 3" gap. With further increase of air gap length, the flux remains practically constant, falling to 10000 lines at 9" gap. This is shown clearly on Plate XXII. This constant value is probably the flux thru stop and coil, and does not affect the pull at all. Hence, it is easily seen why the pull between stop and plunger is negligible after a gap of 1" at most is reached, and has little effect at even smaller lengths.

Referring again to Plates X to XVIII, it is seen that in every case the flux falls as we move the search coil nearer to the plunger. In other words, the center of distribution of flux is nearer to the shell than to the plunger. This falling off is more marked in the planes near the ends of the solenoid. That is, the flux near the ends, instead of following the iron path thru the heads, has a tendency to crowd out thru the coil itself. As the air gap increases, this tendency is more marked.

It should also be noted that as the air gap increases, and the leakage in the planes thru the air gap becomes very great, the flux in planes beyond the air gap does not fall off very much. For example, in Plate XVII, where with a 6" air gap, only 5000 lines pass thru the stop, and practically none thru the air between plunger and stop, the total flux in the plunger remains at 380000 lines. This is a difference of only 20000 lines from the plunger flux with plunger and stop in contact. This bears out the theory that, with a given number of

ampere-turns, the density in the plunger remains constant, no matter what the air gap is. In other words, the sum of the leakage and air gap flux is practically a constant. It may also be noted that except at the ends or near the air gap, the amount of flux in the coil varies directly as the distance from shell to plunger.

The effect of the cast iron heads is also to increase the leakage. This is shown by a comparison of Plates XVI and XIX. The air gap in these two tests was the same, but in Plate XIX the stop was moved up into the coil a distance of three inches. Now in Plate XVI, Planes G and F are the limiting planes of the air gap, and F and E are the limiting planes in Plate XIX. It is seen that the leakage is much greater in the former case than in the latter. This is partly due to the effect of the iron heads,- the tendancy of the flux being to spread out and enter the head rather than enter the stop. The difference is not as great as would appear from the curves, since in the case of the stop projecting into the coil, we have a greater flux in the stop due to the coil surrounding it.

In order to get away from this effect, a set of curves was taken with the air gap always in the center of the solenoid, and the flux at the center of the air gap taken. Plates XXI and XXIII show the results. They show very clearly the uniformity of leakage from plunger to shell with various air gaps.

Applications. Referring to Plate XXIV, curve "a" shows an actual pull curve taken at 11900 ampere-turns. Curve

"d" shows the pull for the same conditions, calcualted by Underhill's formula (6). Itis seen that the two are in close agreement thruout the range of uniform pull. When the air gap is less than two inches, the formula gives a much higher pull than is actually the case. This is due to the fact that the reluctance of the iron circuit has been neglected. Above two inches of air gap it is negligible, but below that it evidently must be taken into account. Now referring to Plate XXV, curve "a" is the actual test curve, while curve "b" is obtained by using Formula (4), but also roughly taking into account the reluctance of the iron portion of the circuit. A very much closer agreement is noticeable. Now curve "c", which agrees almost exactly with "a" from 0 to 1/2" air gap, was obtained by using Maxwell's equation (1), and taking B as the actual flux between plunger and stop, as given by the flux measurements taken. This shows conclusively that the solenoid pull is of little effect up to 1/2" gap, while for larger gaps the plunger and stop pull is almost negligible.

The accuracy of the work done is indicated by the smoothness of the curves obtained. The actual readings are indicated on the curves.

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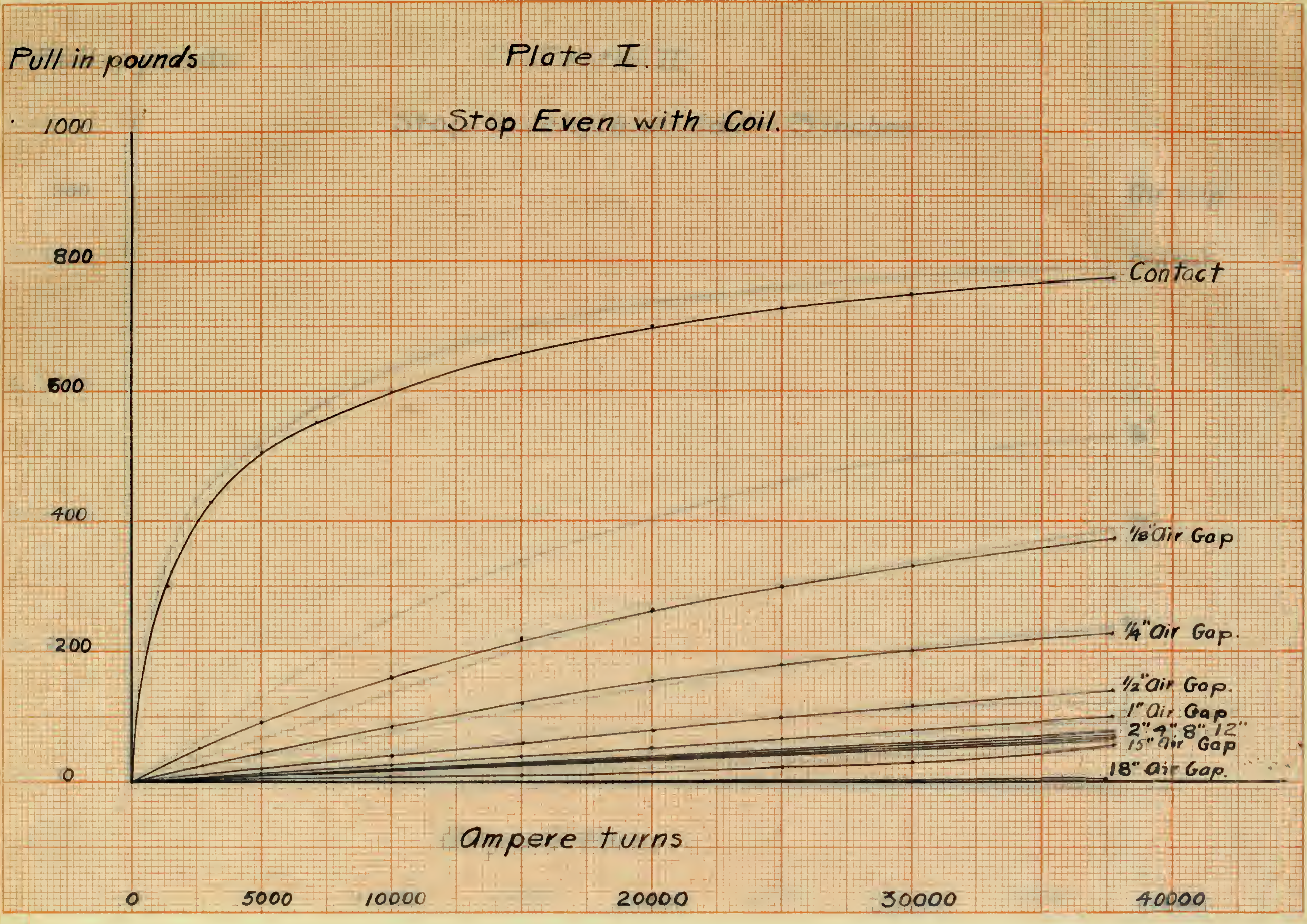
Plate I.



Stop Even with Coil.

Plate II

Stop 1/6 length of Coil – 3 inches.

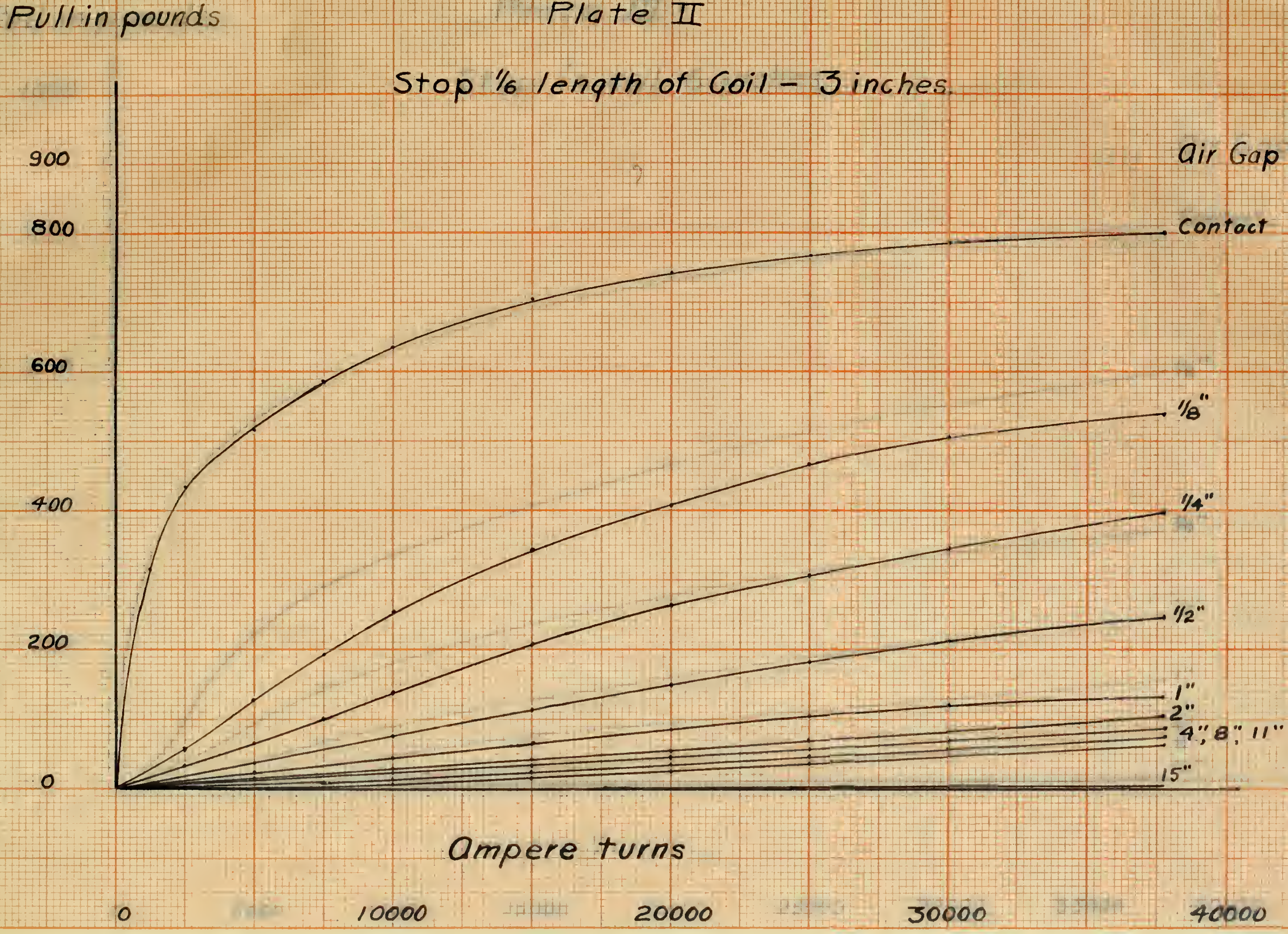


Plate III

Stop in coil 6 inches.

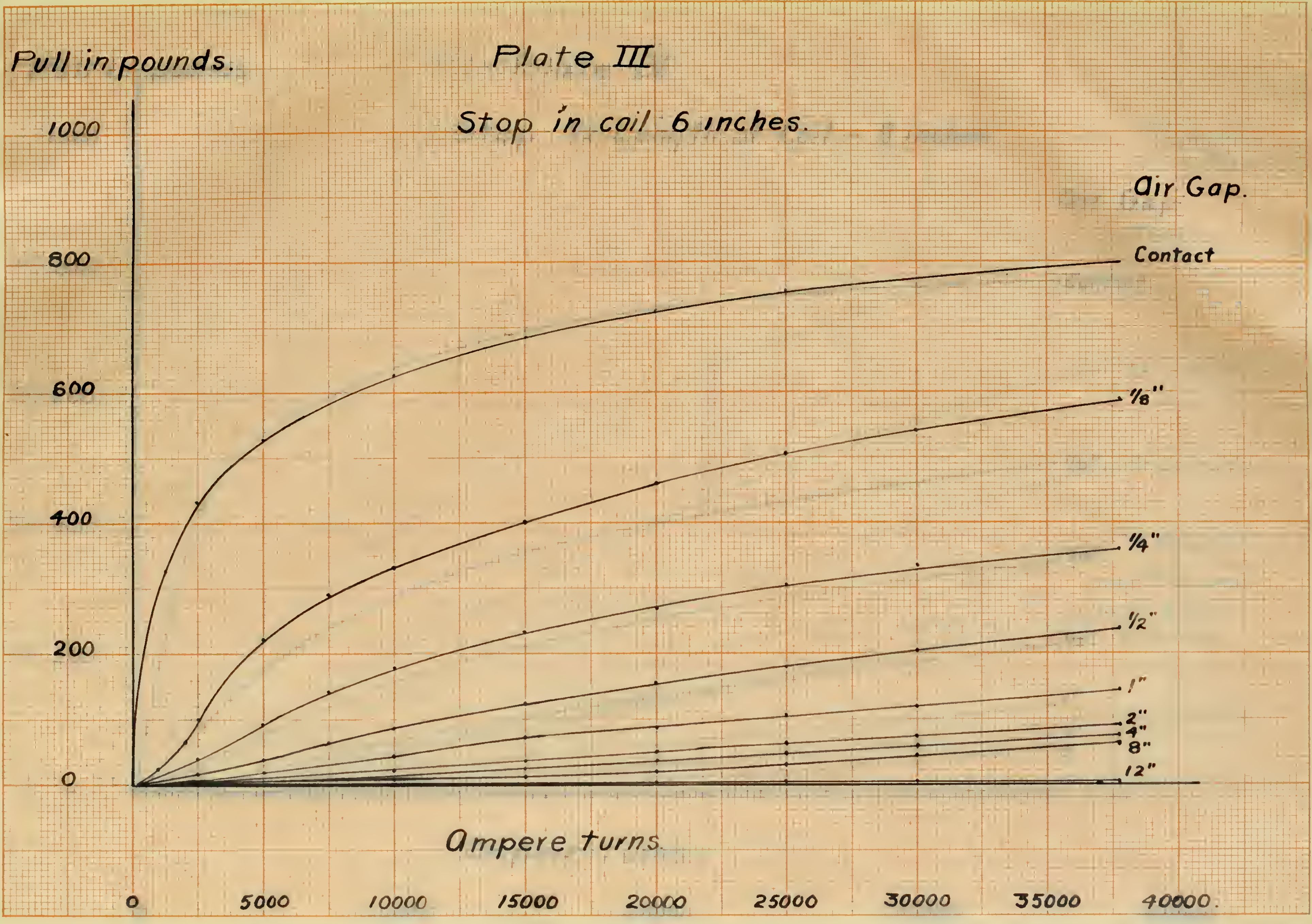


Plate IV

Stop 1/2 Length of Coil – 9 inches.

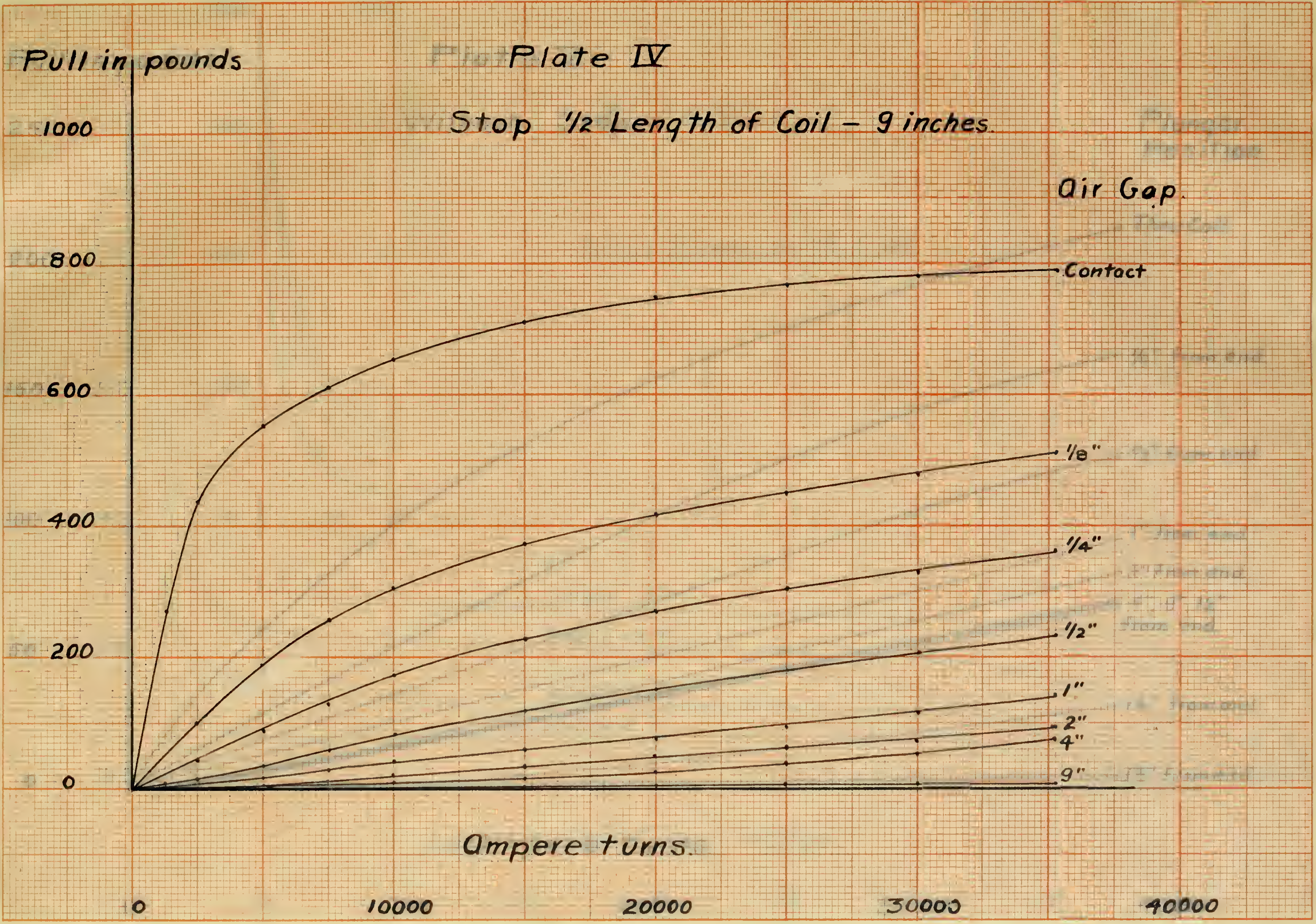
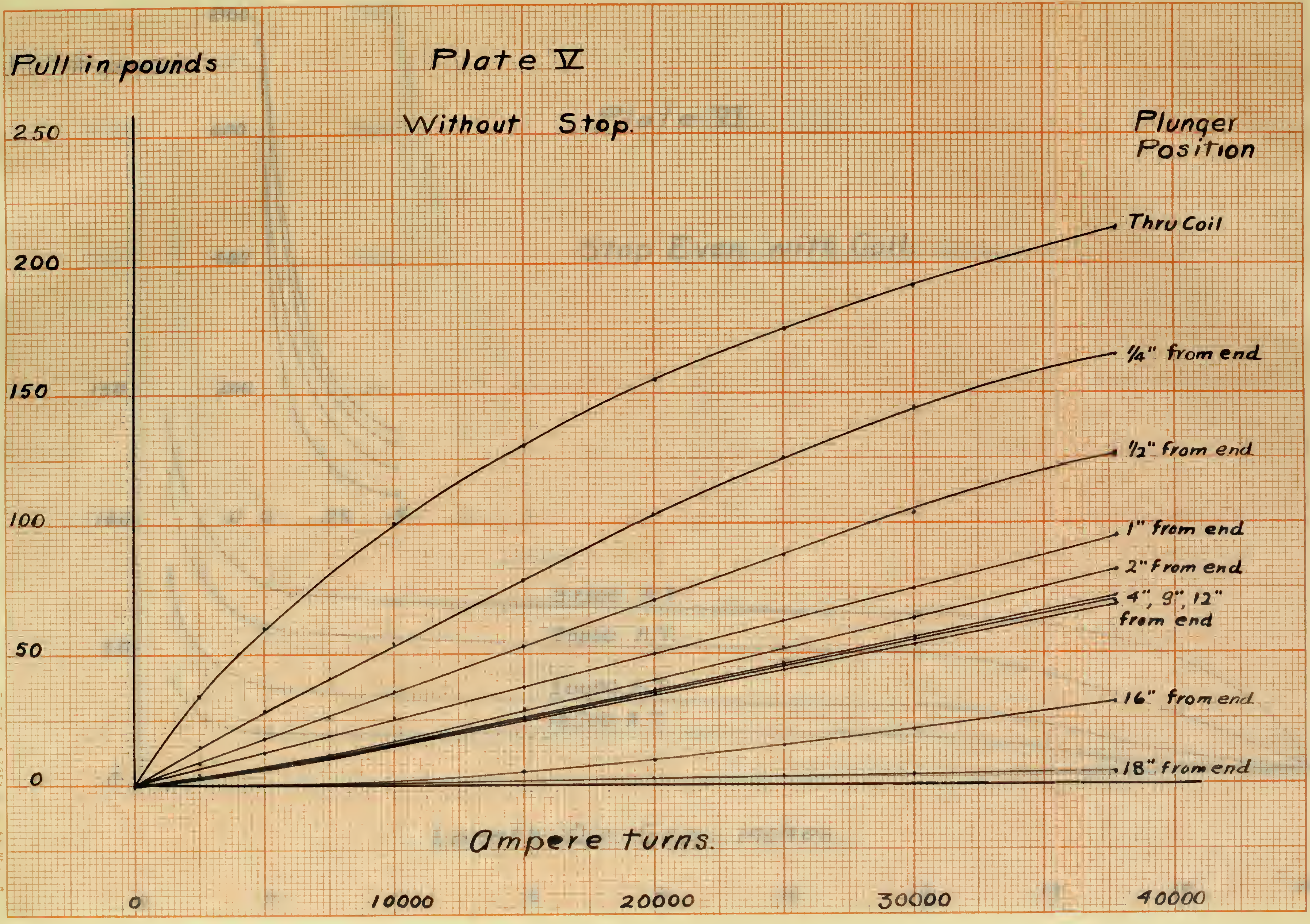


Plate V

Without Stop.



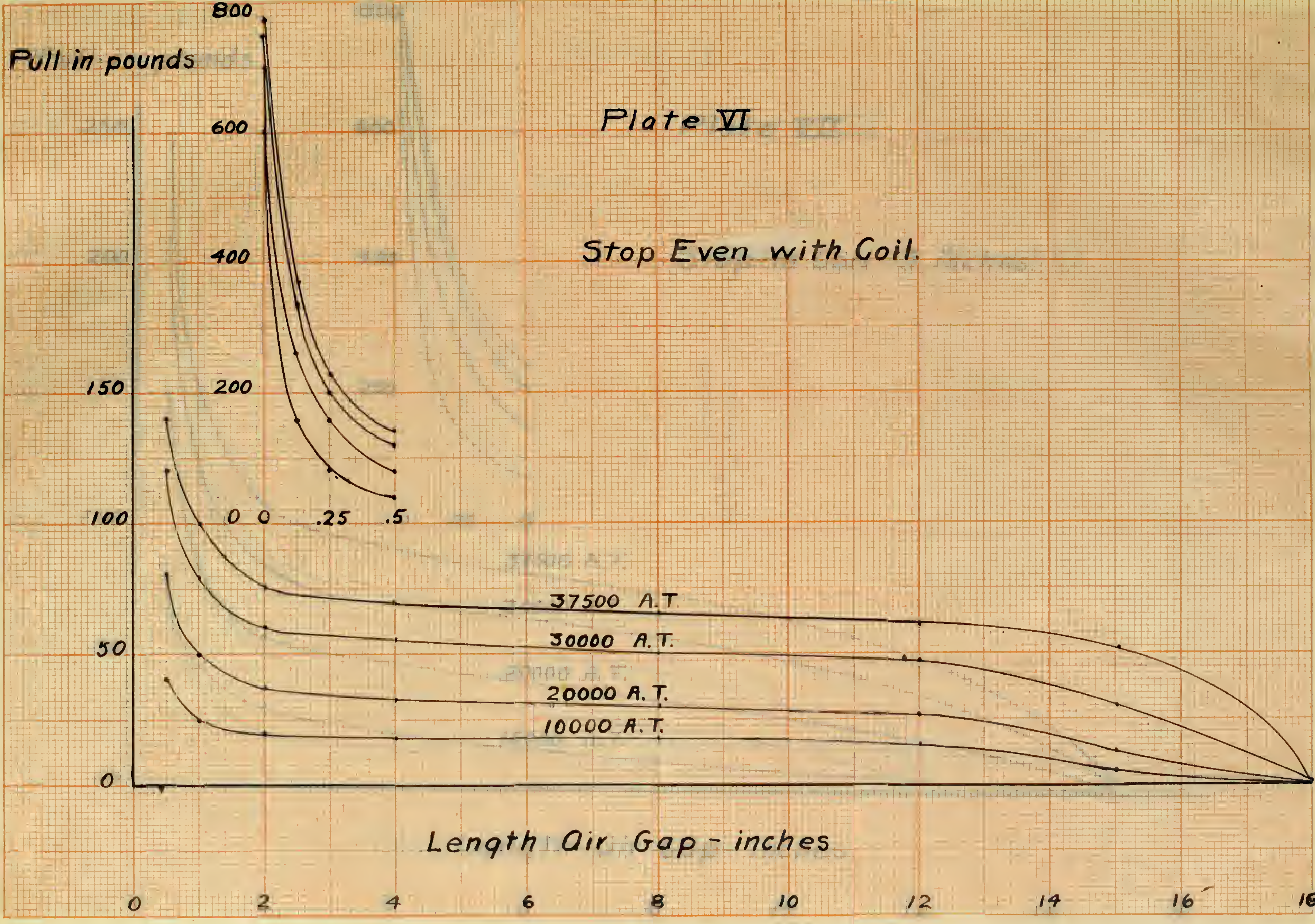


Plate VI

Stop Even with Coil.

Plate VII

Stop in Coil 3 inches.

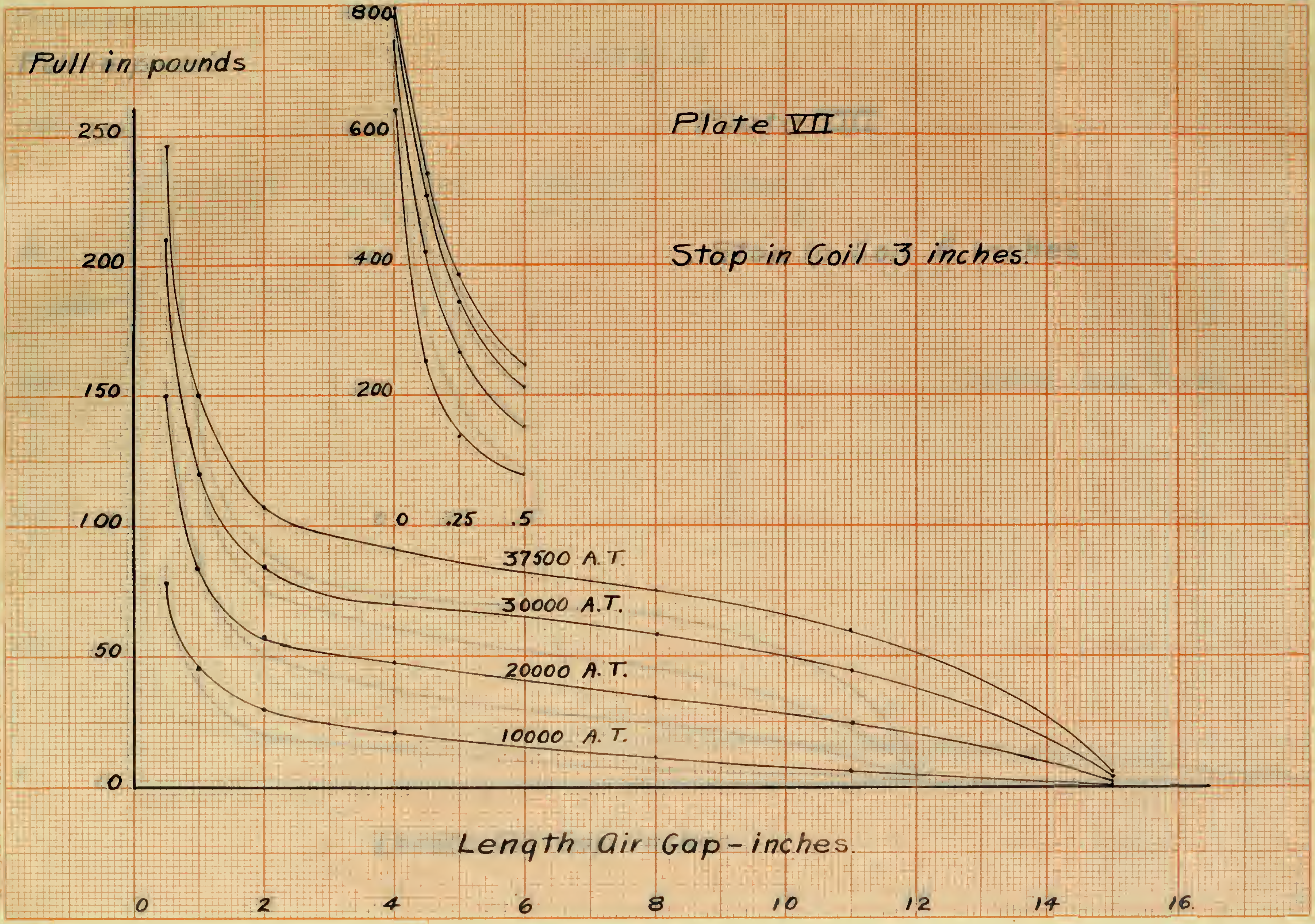
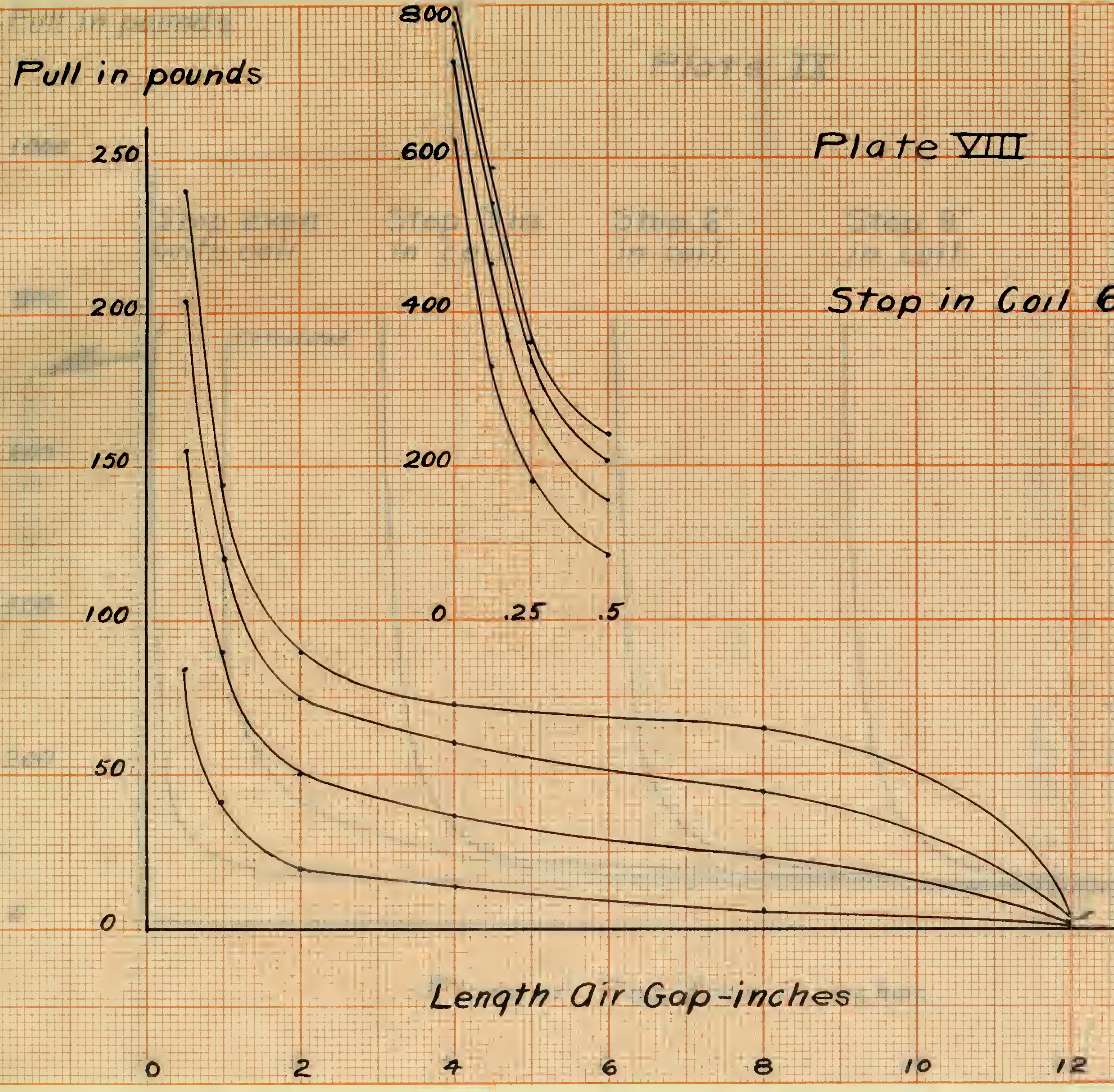


Plate VIII

Stop in Coil 6 inches



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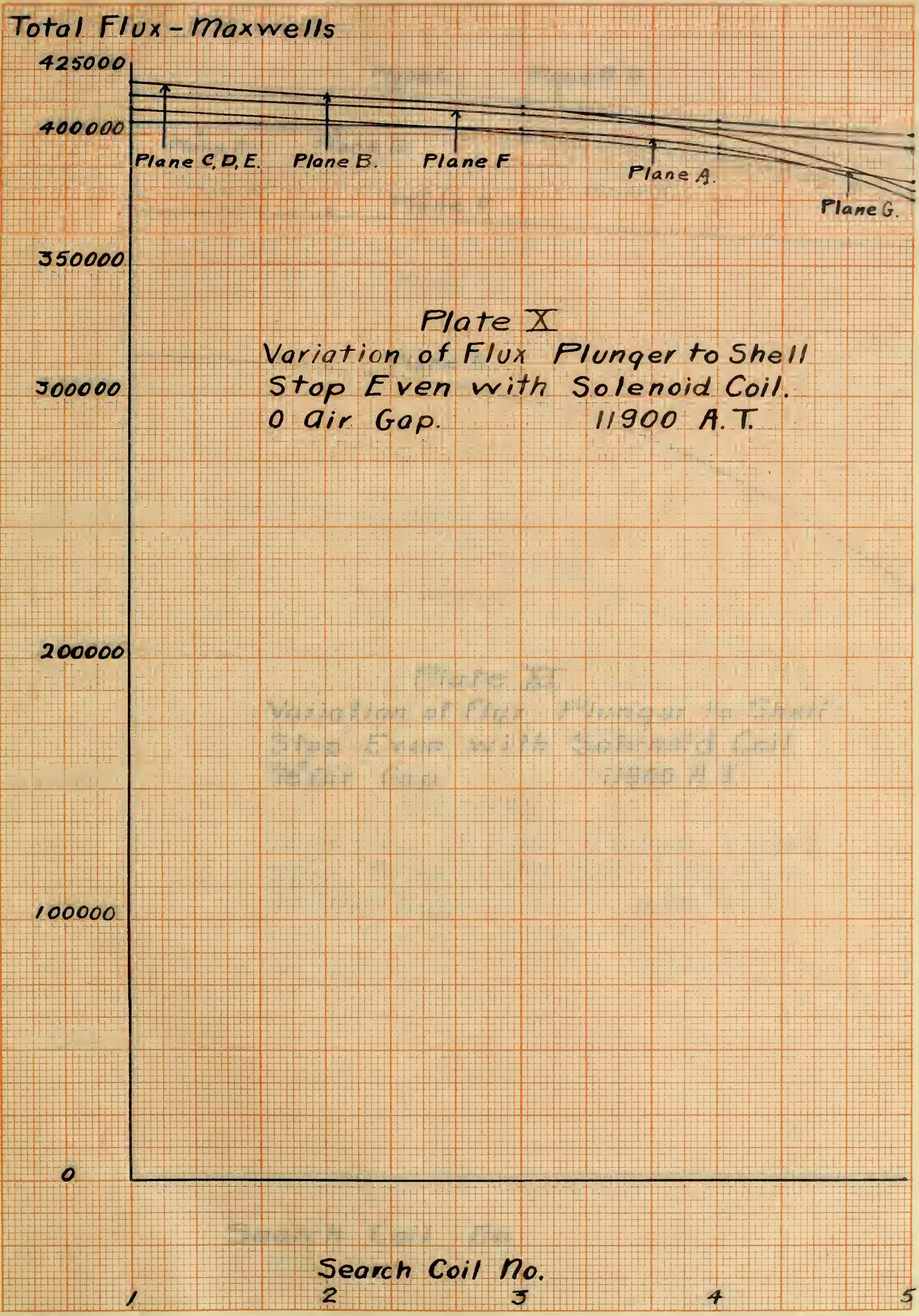


Plate X

Variation of Flux Plunger to Shell Stop Even with Solenoid Coil.

0 air Gap. 11900 A.T.

NO 346

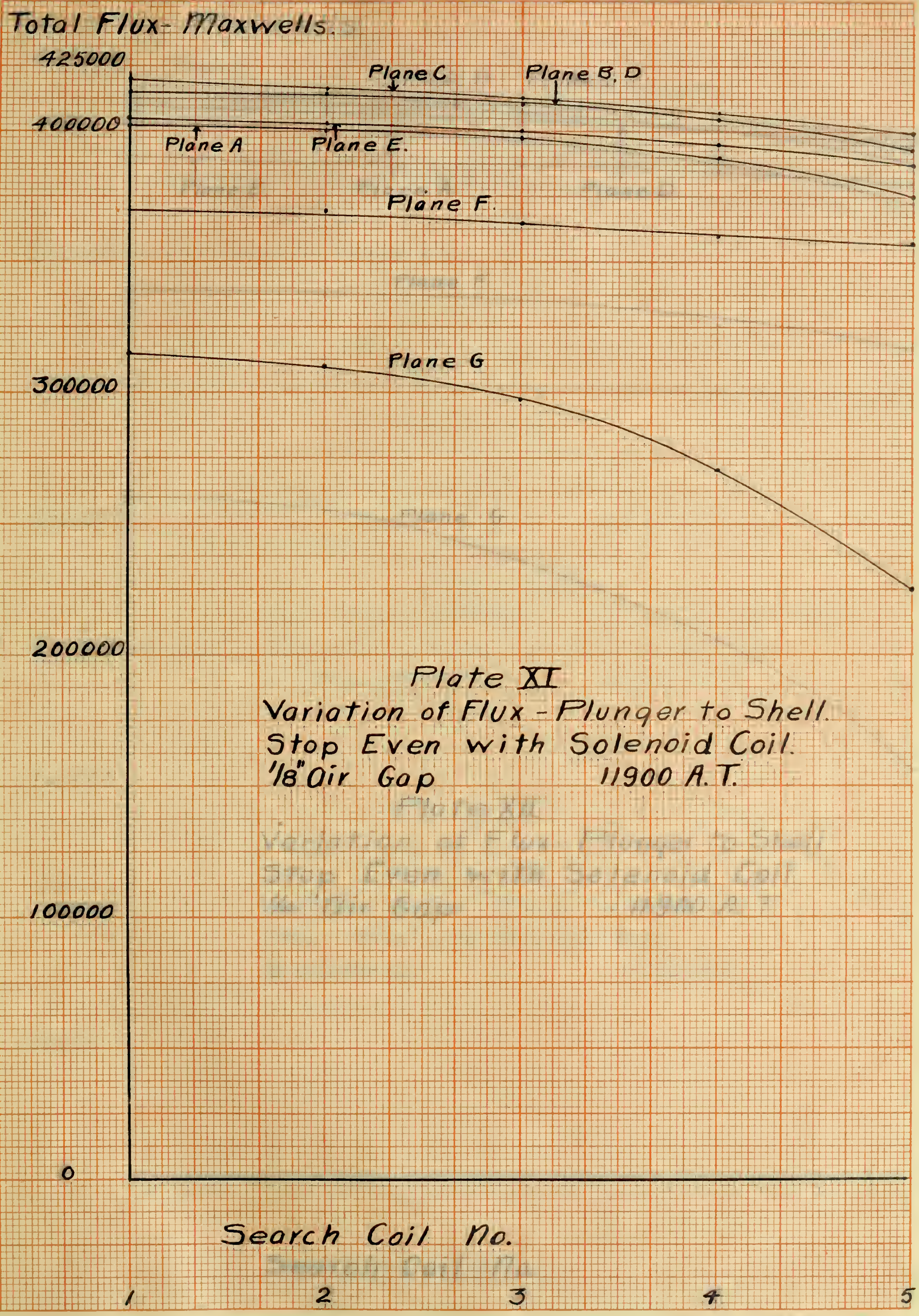


Plate XI
Variation of Flux - Plunger to Shell.
Stop Even with Solenoid Coil.
1/8" Air Gap 11900 A.T.

NO 348

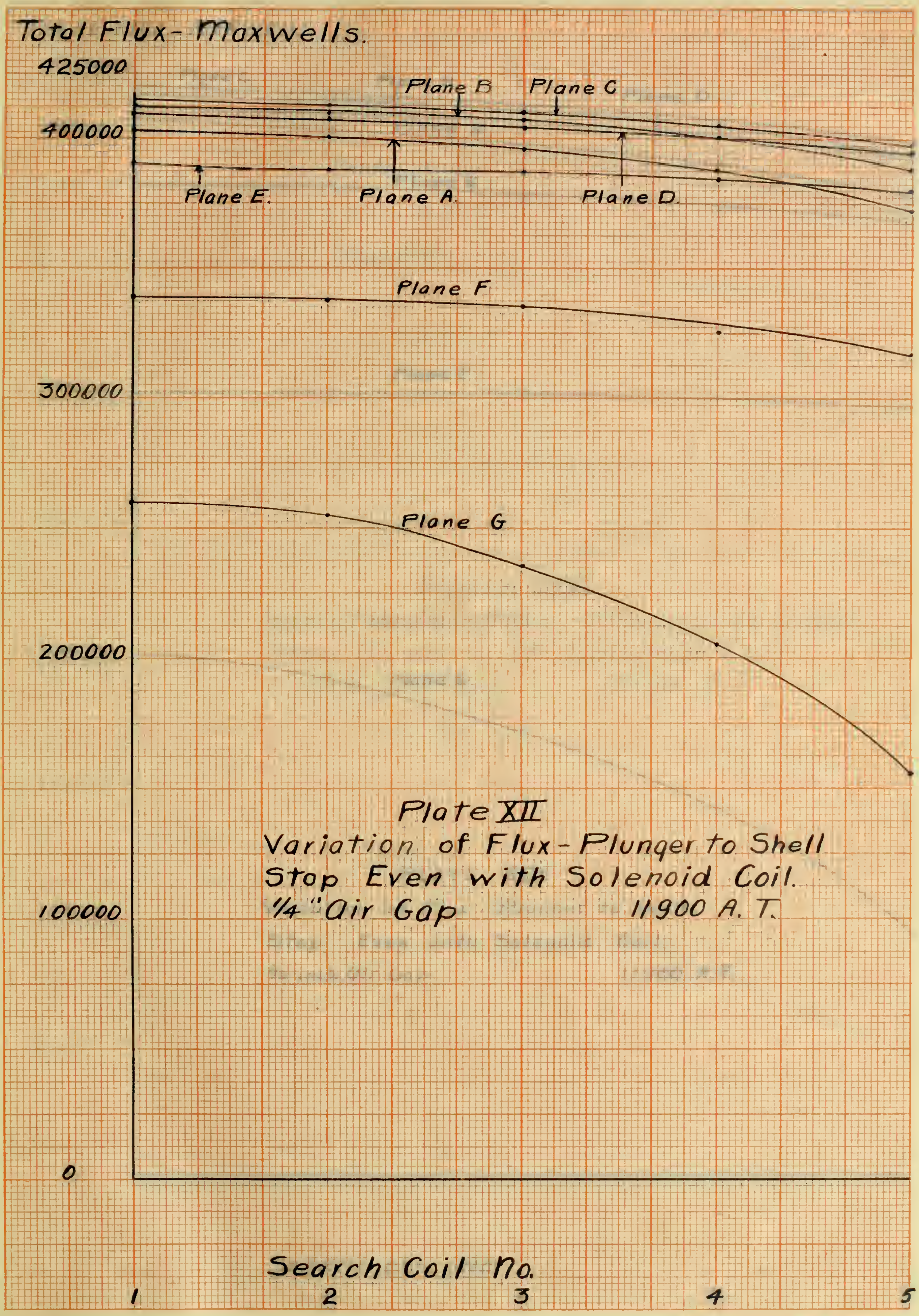


Plate XII
Variation of Flux - Plunger to Shell
Stop Even with Solenoid Coil.
1/4" Air Gap 11900 A. T.

NO 348

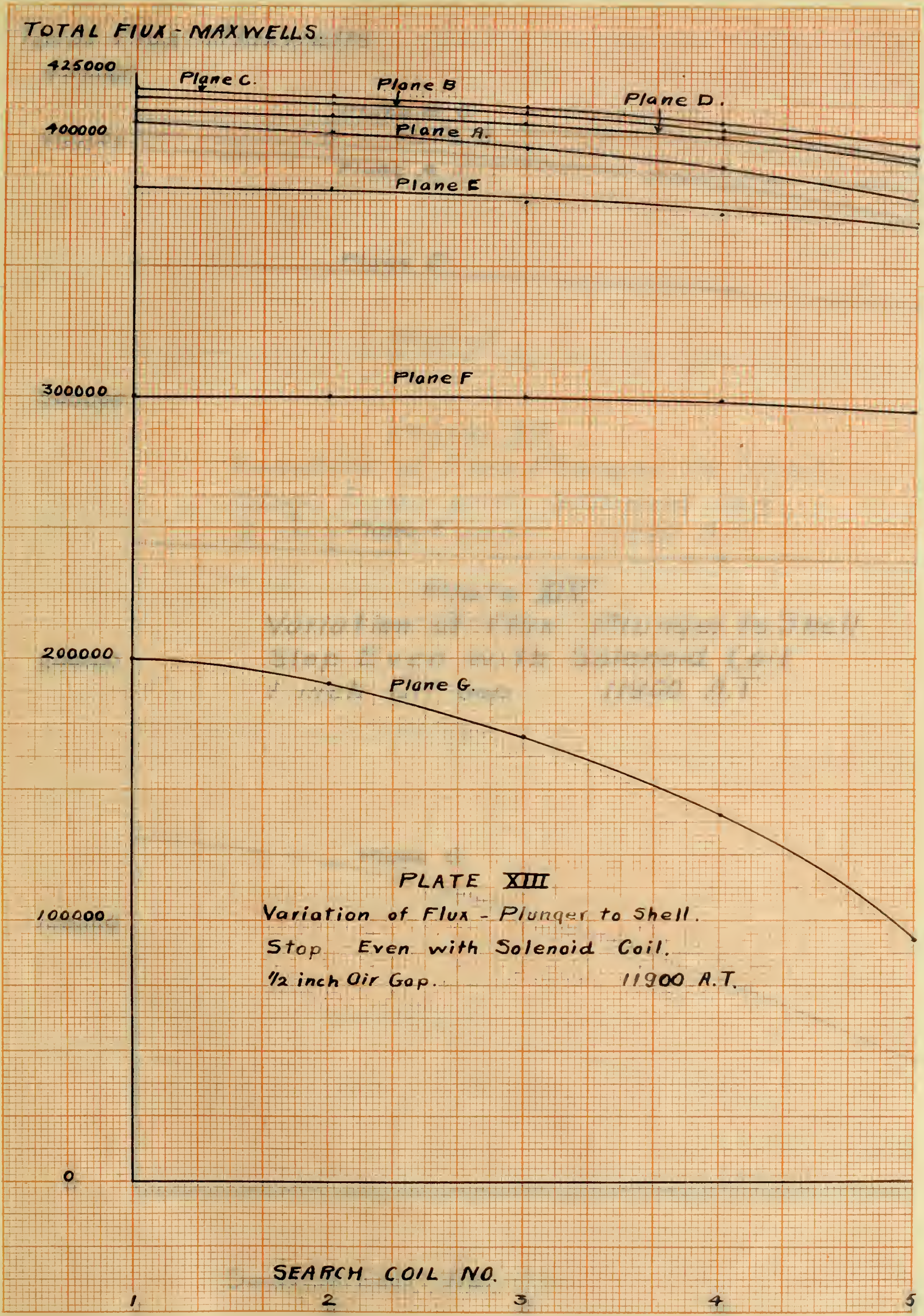


PLATE XIII

Variation of Flux - Plunger to Shell.
Stop Even with Solenoid Coil.
1/2 inch Air Gap. 11900 A.T.

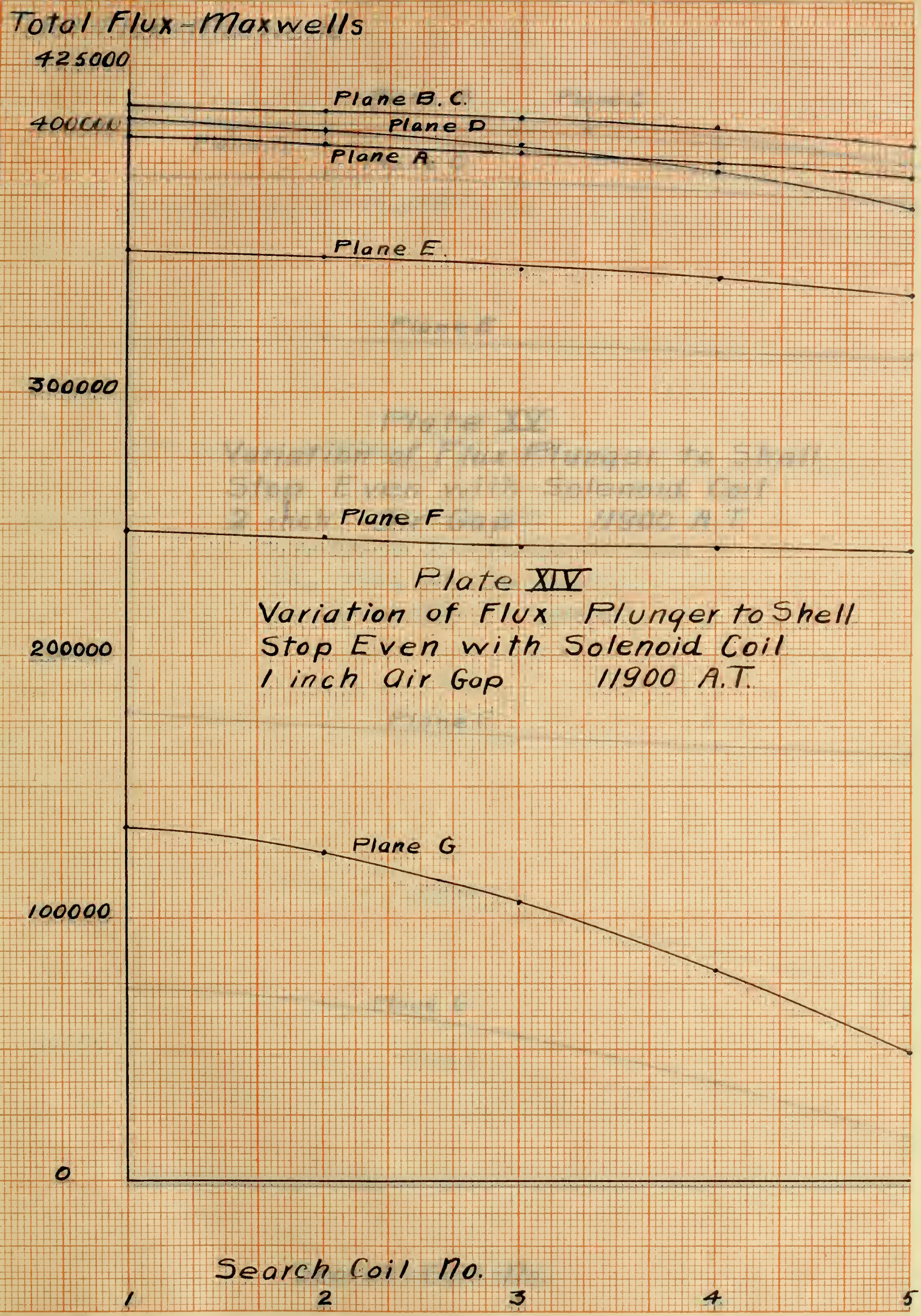


Plate XIV

Variation of Flux Plunger to Shell

Stop Even with Solenoid Coil

1 inch Air Gap 11900 A.T.

NO 346

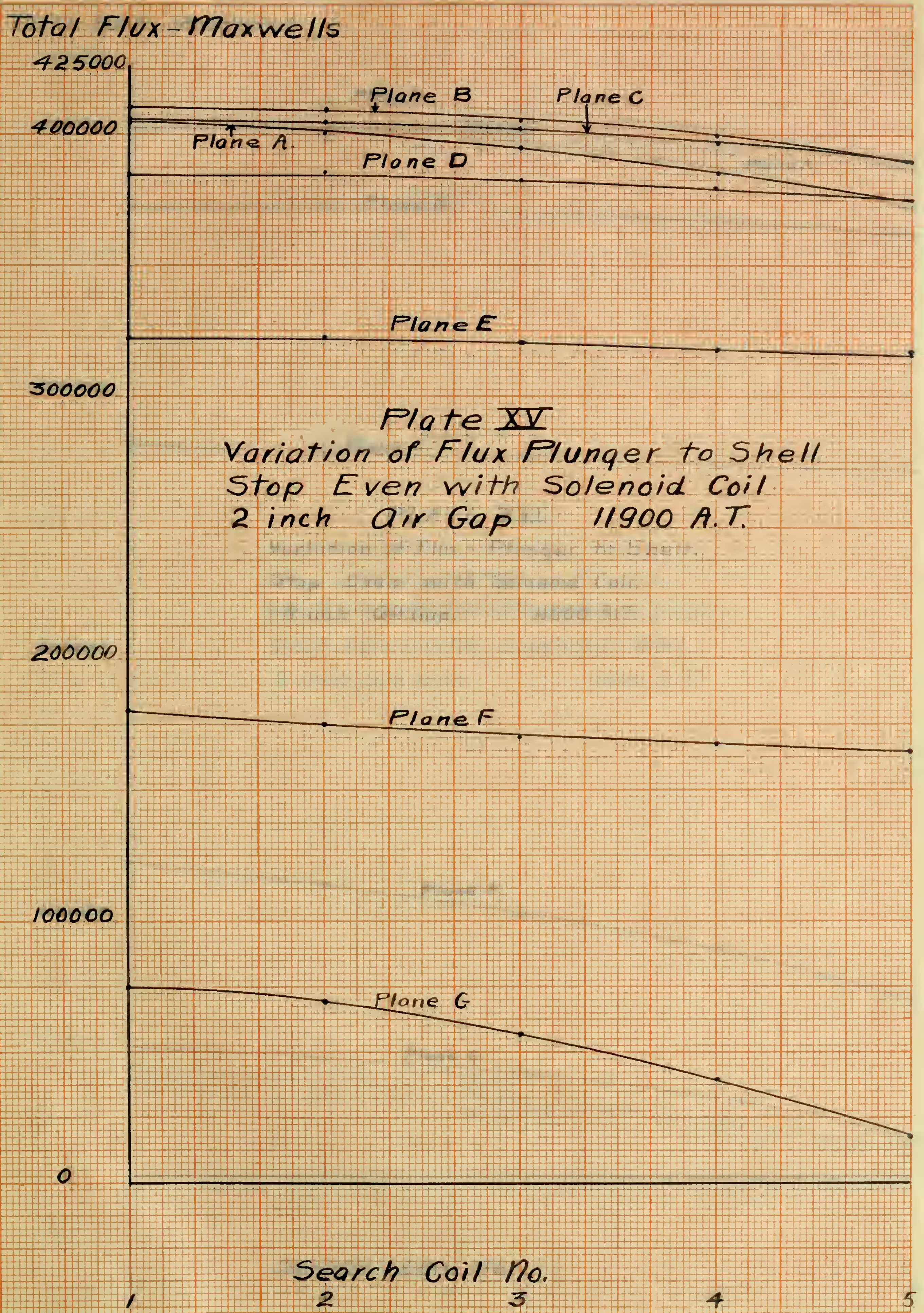


Plate XV
Variation of Flux Plunger to Shell
Stop Even with Solenoid Coil
2 inch Air Gap 11900 A.T.

NO 346 NEW YORK

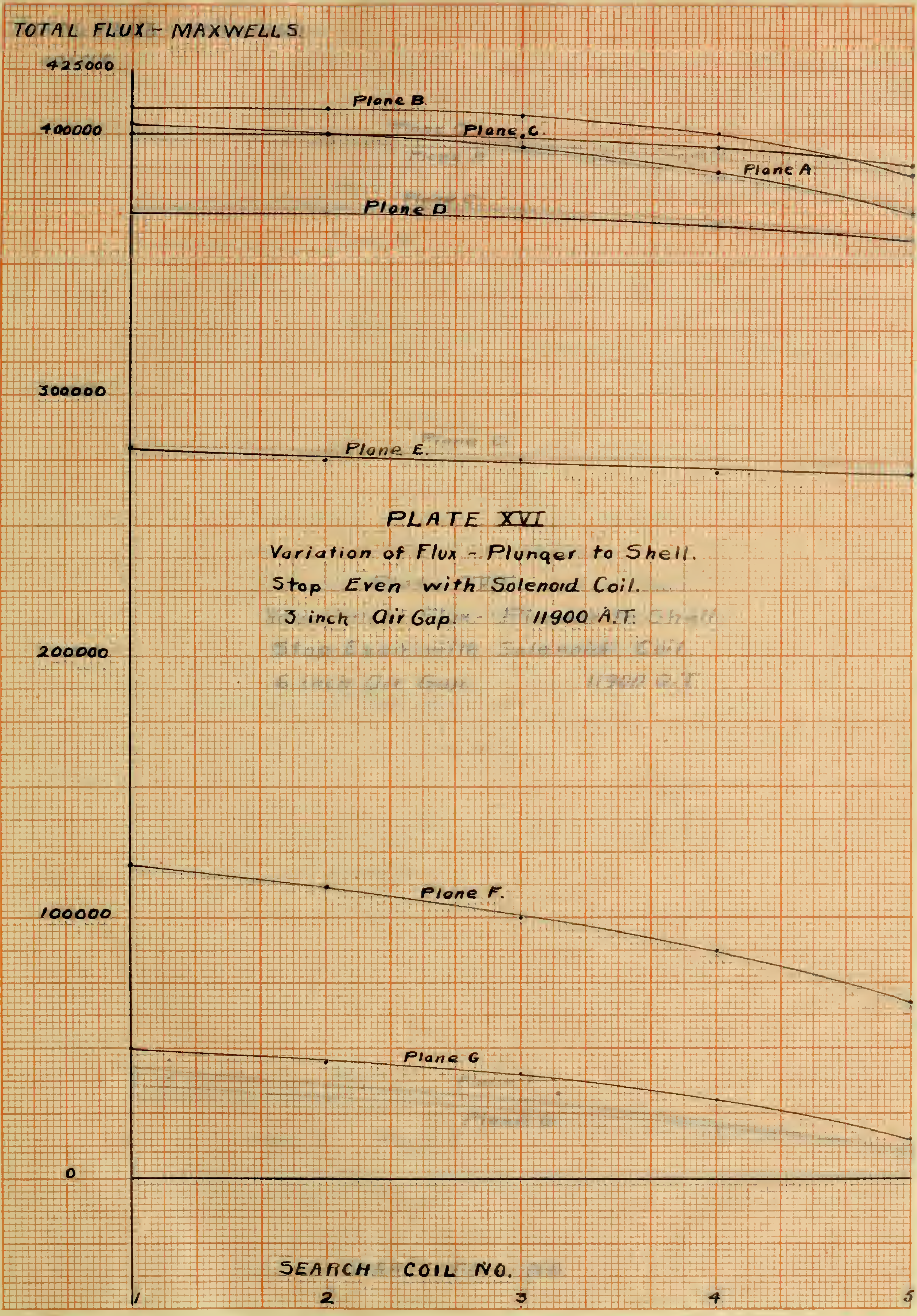


PLATE XVI

Variation of Flux - Plunger to Shell.
Stop Even with Solenoid Coil.
3 inch Air Gap - 11900 A.T.

NO 346

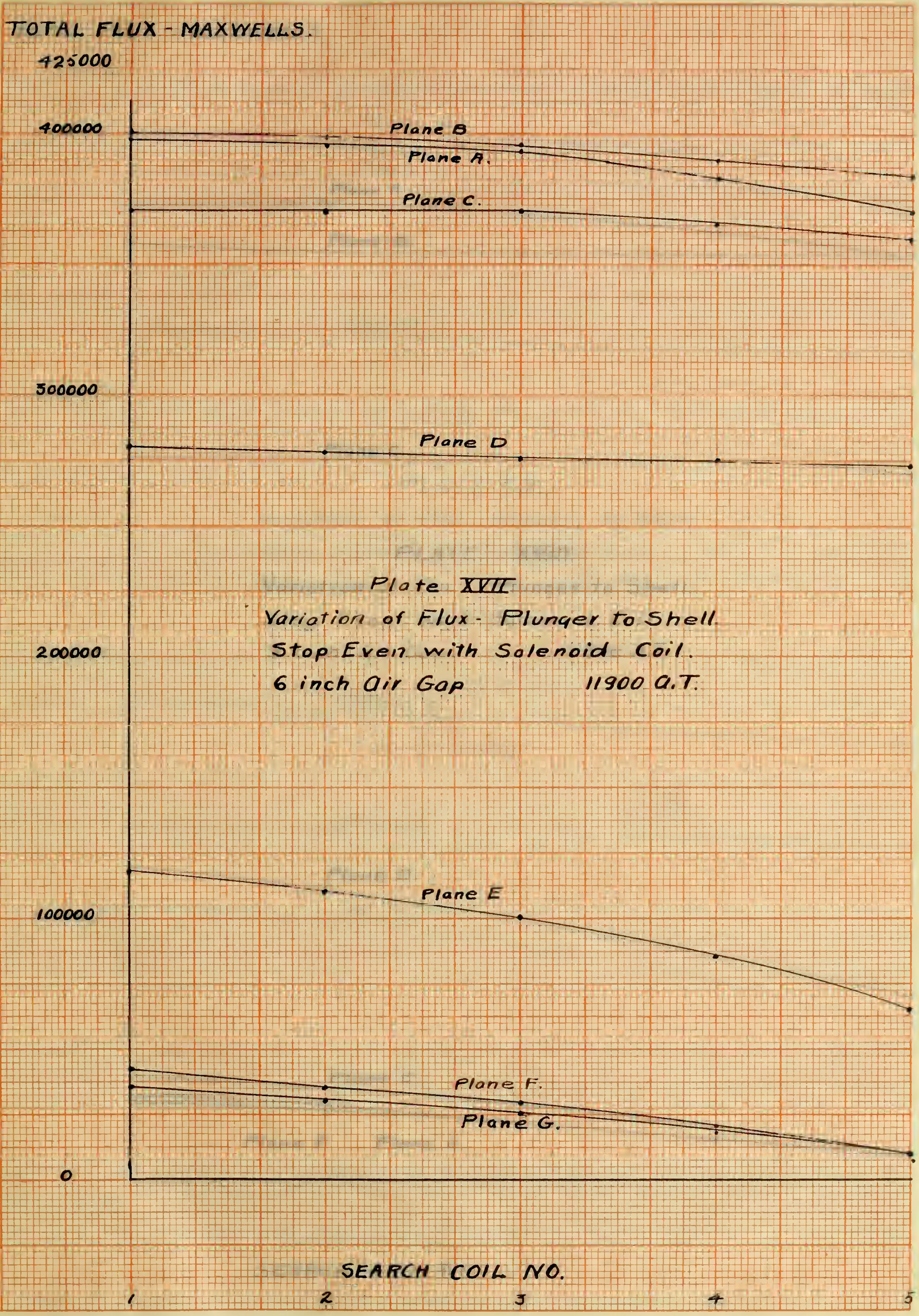


Plate XVII

Variation of Flux - Plunger to Shell

Stop Even with Solenoid Coil.

6 inch Air Gap 11900 A.T.

NO 346
EUGENE DIETZGEN CO. CHICAGO NEW YORK

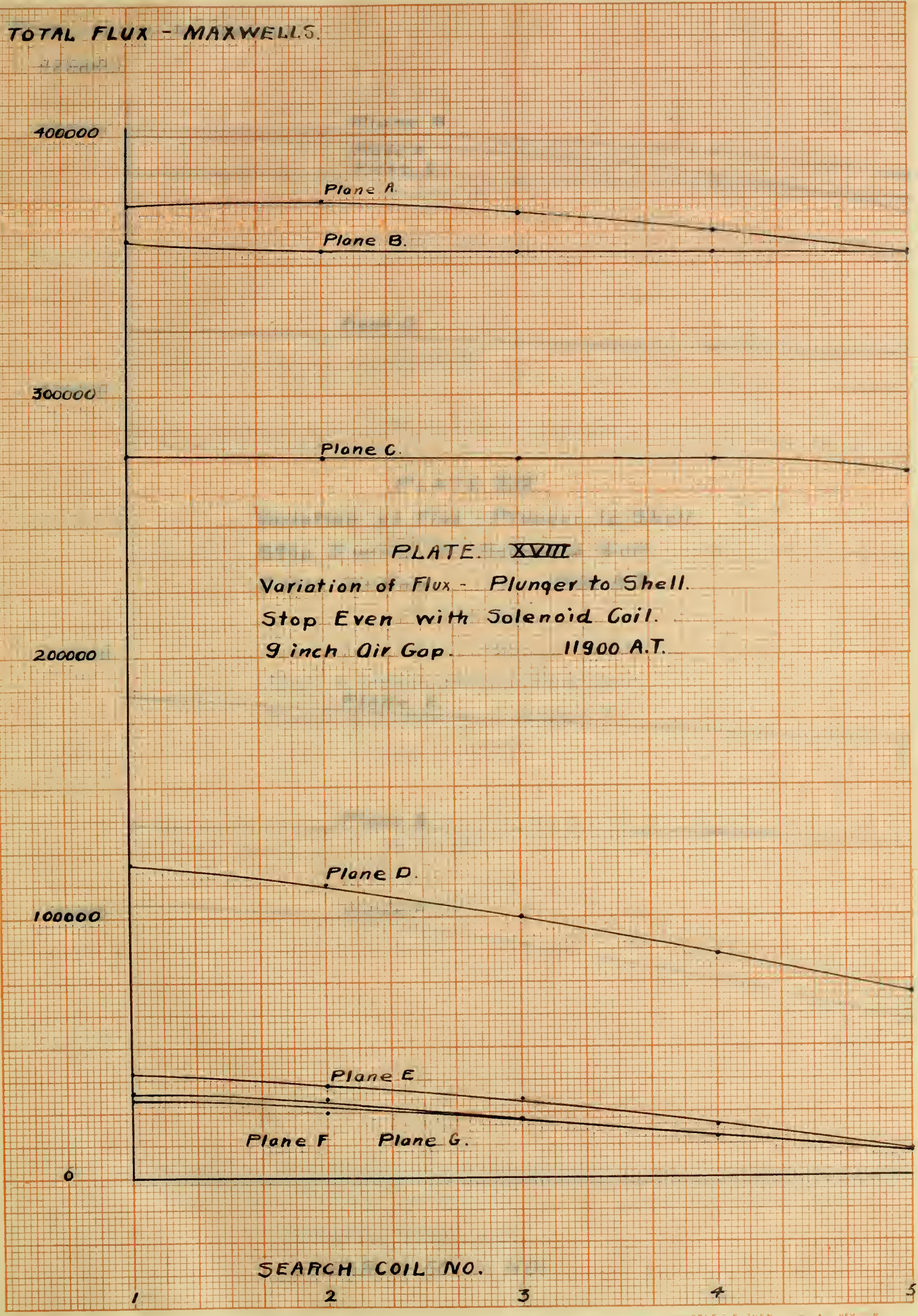


PLATE. XVIII

Variation of Flux - Plunger to Shell.

Stop Even with Solenoid Coil.

9 inch Air Gap. 11900 A.T.

NO 346

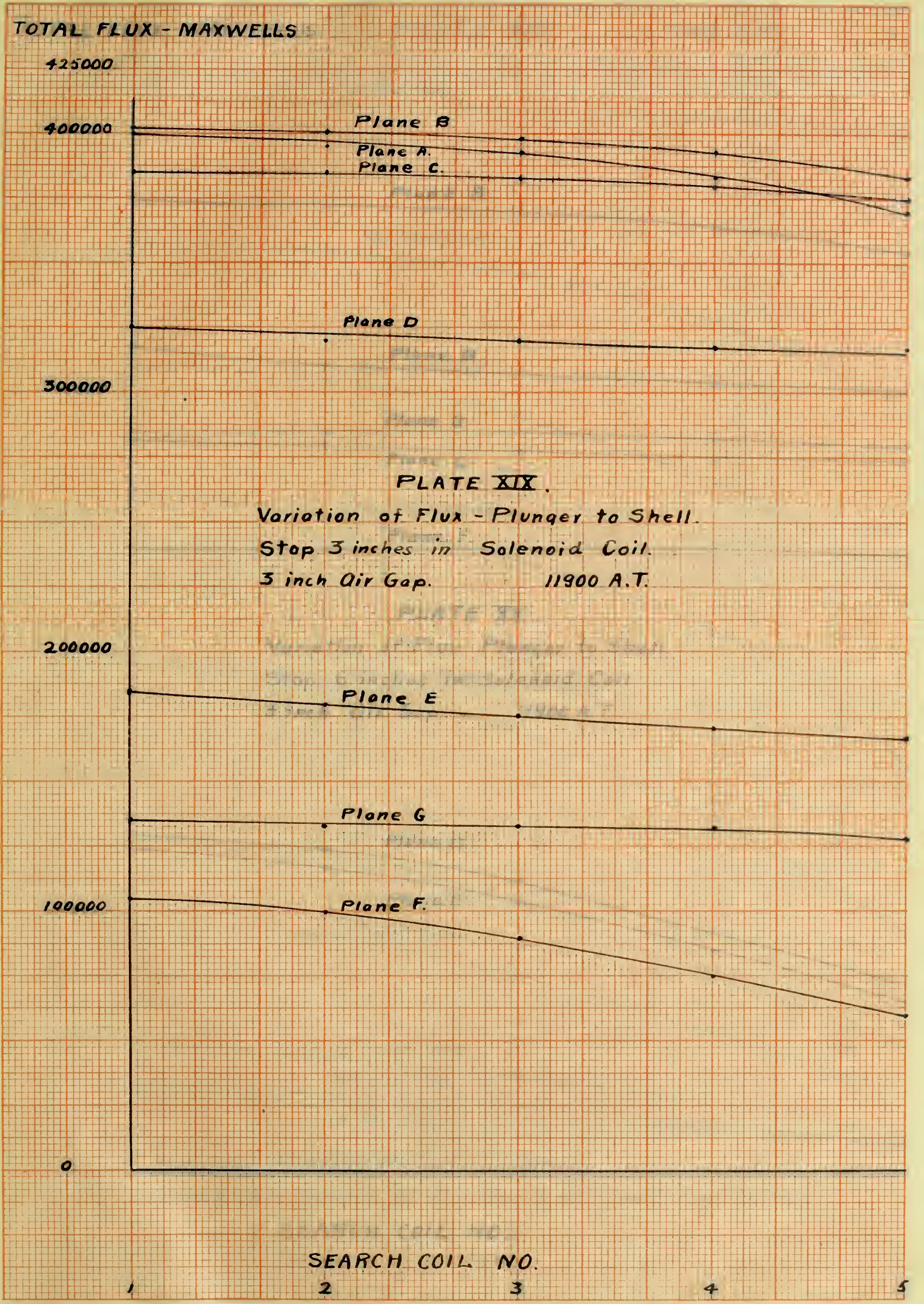


PLATE XIX.

Variation of Flux - Plunger to Shell.

Stop 3 inches in Solenoid Coil.

3 inch Air Gap. 11900 A.T.

NO 346

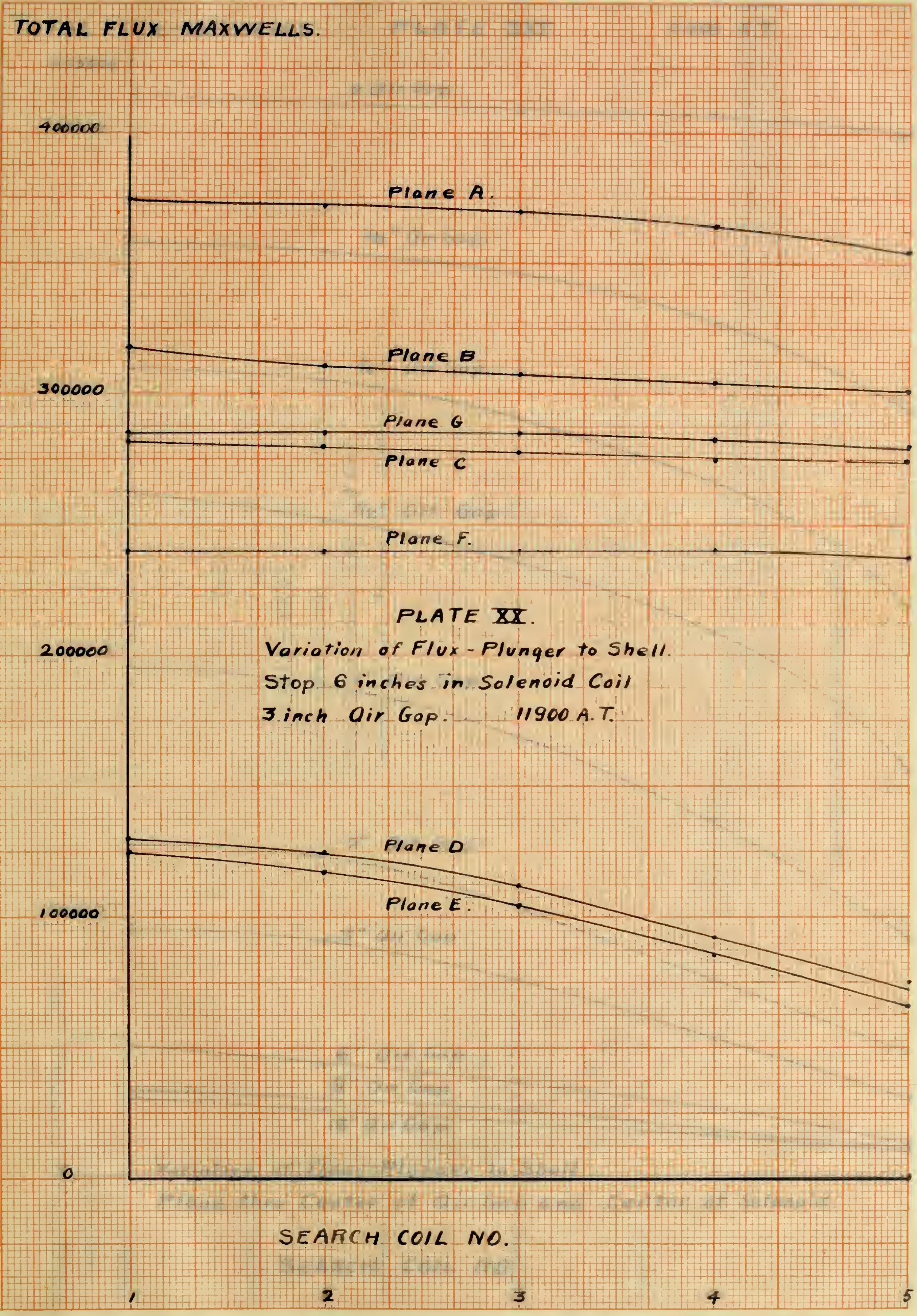
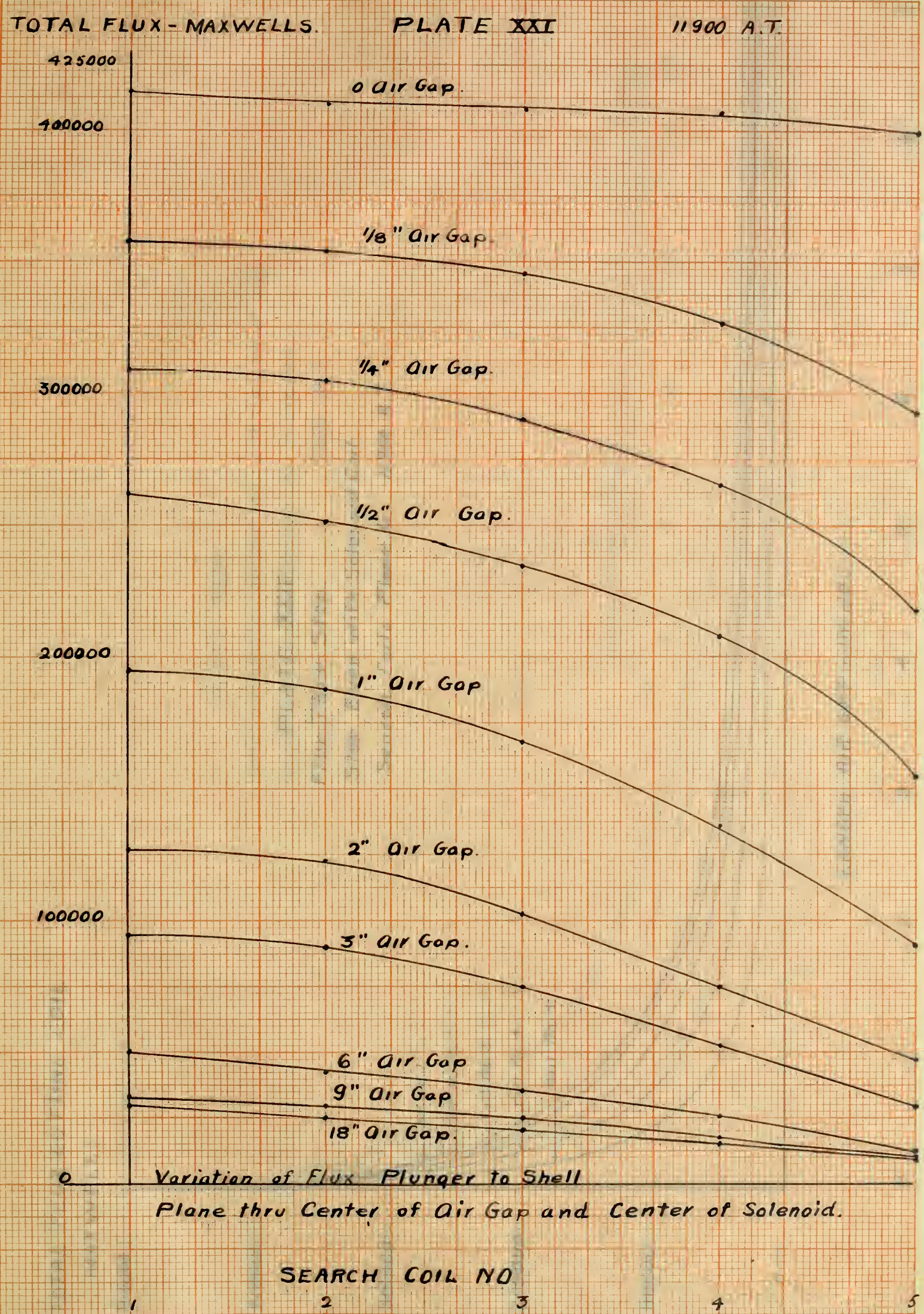


PLATE XX.

Variation of Flux - Plunger to Shell.
Stop 6 inches in Solenoid Coil
3 inch Air Gap. 11900 A.T.

PLATE XXI



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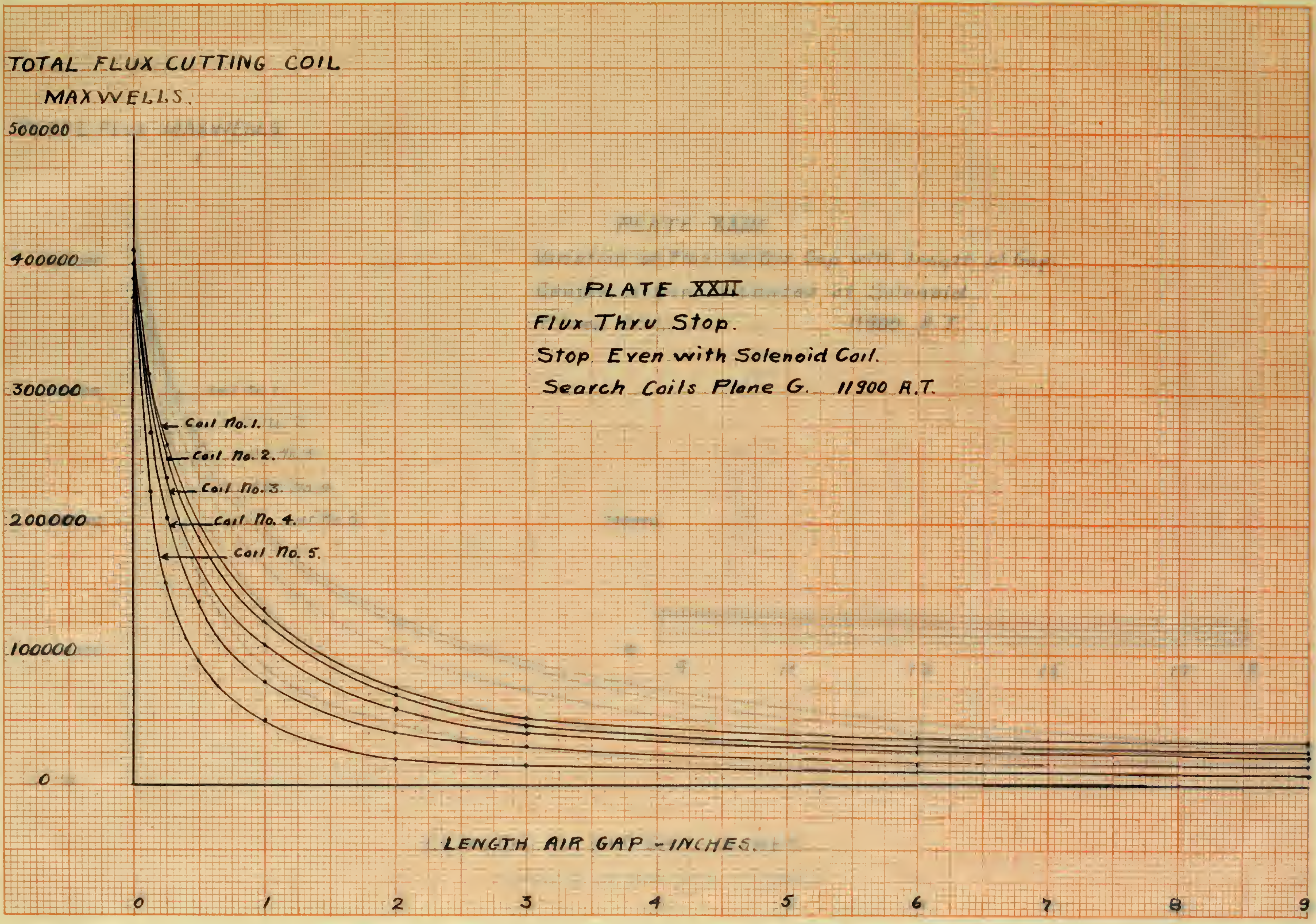


PLATE XXII

Flux Thru Stop.

Stop Even with Solenoid Coil.

Search Coils Plane G. 11900 A.T.

NO 346

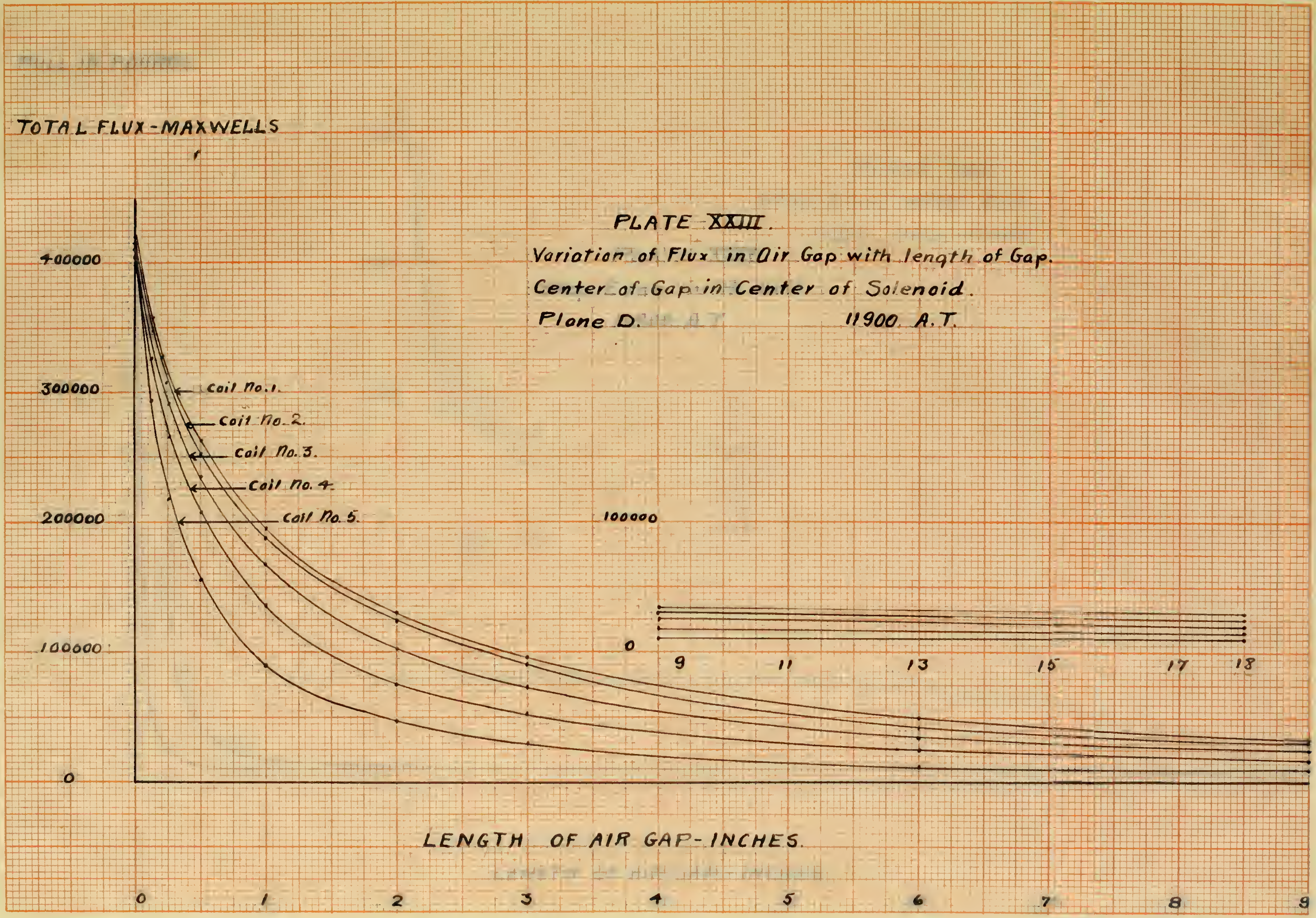


PLATE XXIII.

Variation of Flux in Air Gap with length of Gap.

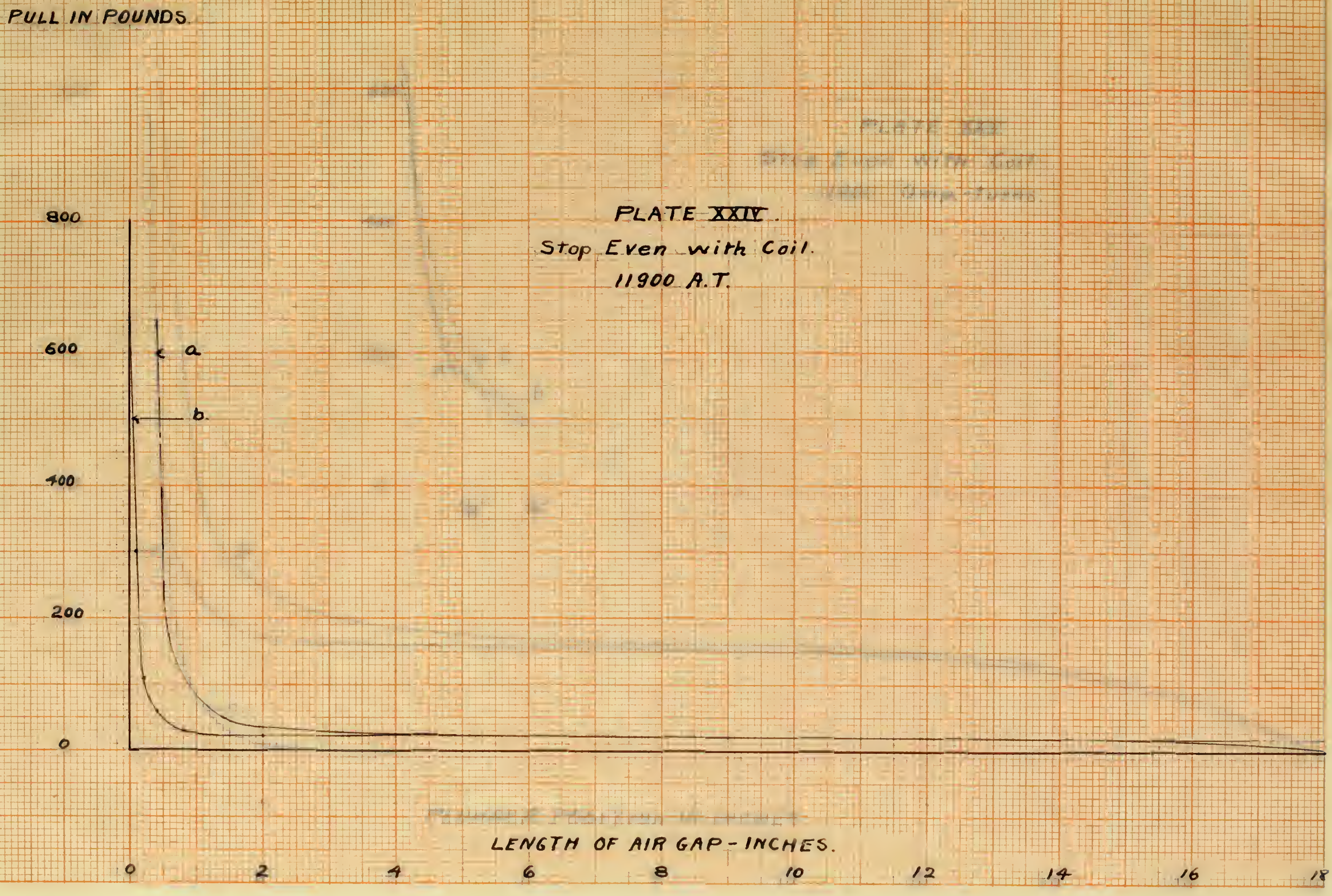
Center of Gap in Center of Solenoid.

Plane D. 11900 A.T.

PLATE XXIV.

Stop Even with Coil.

11900 A.T.



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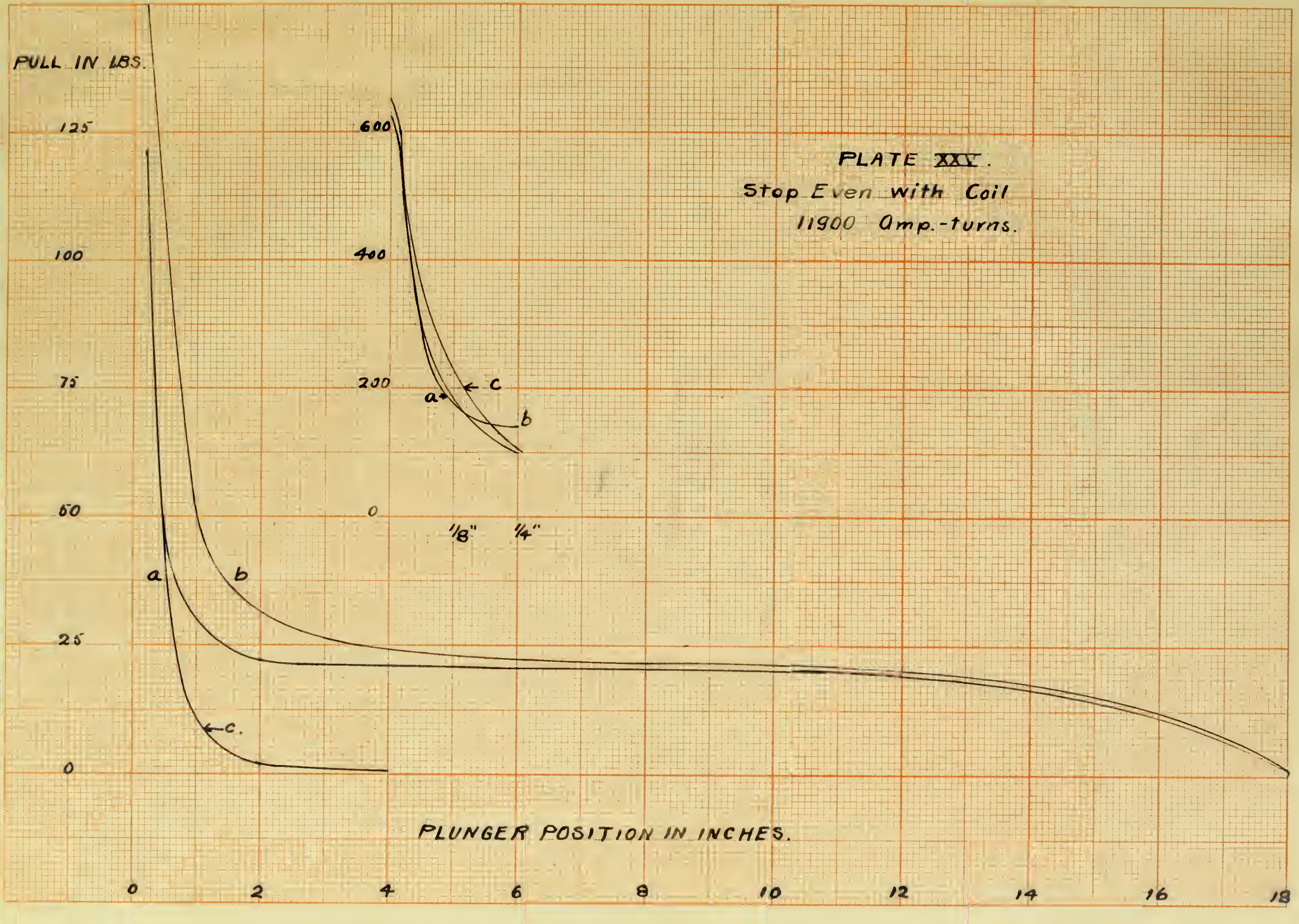

PLATE XXV.

Stop Even with Coil

11900 Amp.-turns.

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